Renewable and Sustainable Energy Reviews 39 (2014) 174–195

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Different aspects of dry anaerobic digestion for bio-energy: An overview

Richa Kothari [a,*], A.K. Pandey [b], S. Kumar [b], V.V. Tyagi [c], S.K. Tyagi [b,*]

[a] School of Environmental Sciences, Babasaheb Bhimrao Ambedkar University, Lucknow 226025 (UP), India
[b] Sardar Swaran Singh National Institute of Renewable Energy, Kapurthala 144601 (Punjab), India
[c] Department of Physics, Manav Rachna College of Engineering, Faridabad 121001 (HR), India

ARTICLE INFO

Article history:
Received 7 September 2012
Received in revised form
20 September 2013
Accepted 6 July 2014
Available online 31 July 2014

Keywords:
Biogas production
Biomass waste
Dry anaerobic digestion
Environmental pollution
Contents

ABSTRACT

Dry anaerobic digestion (DAD) is an attractive method for the stabilization of solid organic waste with high solid concentration (22–40%). This article provides different aspects for bio-energy production through dry anaerobic digestion suggested by different researchers. Basic fundamental aspects like reactions occurring in the process, microbial species involved in the process, effect of feedstocks and operational parameters like pH, temperature, C/N ratio, VFA concentration, etc. with types of reactors are summarized. A number of scenarios and the effect of changing individual parameters of the environmental impacts of dry anaerobic digestion process for biogas production are considered. Mobility of mass nutrient and energy flow in the above said process are also parts of this review article. We conclude that long term research and development for improvement and optimization of operational parameters in dry anaerobic digestion is necessary.

Contents

* Corresponding authors.
E-mail addresses: kothariricha21@gmail.com (R. Kothari), sudhirtyagi@yahoo.com, sktiitd@gmail.com (S.K. Tyagi).

http://dx.doi.org/10.1016/j.rser.2014.07.011
1364-0321/

1. Introduction

Anaerobic digestion (AD) is a biological process that converts organic matter into a methane rich gas. It is a well established technology for the treatment of organic fraction of various waste materials [1–3]. Water has an important role in the controlling of the whole AD process. It is responsible for the growth of microbial population and also worked as a buffering agent for all the substrate and reactants. The AD process are classified in different ways such as on the basis of the reactor design, operating parameters such as pH, total solids (TS), volatile solids (VS) contents and biodegradability of substrate. In order to facilitate the above said process, recommended percentage of total solid in digester, can be categorized i.e. with low ($<15\%$), medium (15–20%) and high (20–40%) total solids [4–6]. Therefore, the wet anaerobic digestion system are characterized by total solids less than that 15% and dry system are characterized by total solids higher than 15%.

However, AD was found to be an attractive method especially in present time because it offers a spectrum of striking advantages [5]. This technology is very salient in Asian countries because of its suitable waste characteristics. Thus, anaerobic treatment provides a method of reducing pollution from various operations (agricultural, municipal and industrial operations). Among the biological treatments, AD is the most cost-effective, owing to the high energy recovery linked to the process and its limited environmental impact [6]. This process is considered as innovative and attractive technology for waste stabilization with significant mass and volume reduction with the generation of valuable by products such as biogas and fertilizer. The anaerobic digestion of biomass waste is now an established and commercially proven approach for treatment and recycling [7].

Wet Digestion requires the huge amount of water, which may be either equal or greater than the quantity of biomass. This result in a huge wasting of water, which should be avoided taking into consideration the condition of water scarcity in India. Also the high percentage of water present in the digested slurry severely decreases per unit volume nutrient value of manure, which hampers the transportation economics of manure. Drying of manure involves huge requirement of land and energy and also loss of its nutrient value. In this view, dry anaerobic digestion (DAD) is a process that is rapidly gaining momentum to new advances especially in the area of anaerobic fermentation and has become a major focus of interest in waste management throughout the world. The DAD performance is very robust as it allows very high production rates [8]. This process is more feasible to wide range of organic wastes including wastewater sludge from industries with the recovery of renewable energy and reduction in pollution load [9]. Application of this process is limitedly practiced especially in developing countries due to the lack of appropriate treatment system configurations and mainly due to the longer time required for the bio-stabilization of waste. In this regard, DAD is remarkable method that could offer potential by-products such as fertilizer and energy generation. The process also results in a lower production of leachate and easy handlings of digested residues that can be further treated by aerobic composting processes are used as organic fertilizer [10].

Dry Anaerobic Digestion (DAD) process is more popular nowadays among researchers and in corporate sector for laboratory scale and pilot studies because of its reduced cost and potential by-products. But, sometimes the process shows inhibition problem [11], which may be due to requirement of large amount of inoculums, long retention time [12], accumulation of VFA [13] and type of complex solid waste materials [14]. Therefore, to develop a suitable and feasible DAD process, it is important to review and suggest the improvement required for the sustainable approach. In this regard, various aspects of the process, operational parameters, environmental impacts of the process, economic analysis, mass balance and energy flow have been included in this article.

2. Basic kinetics involved in process

Anaerobic digestion of organic matters occurs in four steps, called as hydrolysis; acidogenesis; acetogenesis; and methanogenesis. There is a consortium of microorganisms such as acidogenic bacteria, acetogenic bacteria, and methanogens, etc., which are responsible in biogas production from organic materials. The organic matters are found in any waste in the form of polymers such as carbohydrates (cellulose, hemicelluloses, starch, etc.), oils, fats and proteins. In general, microorganisms are not capable to utilize these polymers because of large size of molecule, which cannot penetrate the cell wall of the microorganisms. Therefore, acidogenic bacteria produce extracellular enzymes such as cellulose, xylanase, amylase, lipage, proteolytic enzymes, etc., to hydrolyze these polymers. The carbohydrates, proteins and oils and fats are hydrolyzed into monomeric sugars, amino acids and fatty acids, respectively. An approximate chemical formula for the mixture of organic waste is $C_6H_{10}O_4$ [15]. The hydrolysis reaction can be written as [15]:

$$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + H_2 \quad (1)$$

The hydrolyzed organic compounds (monomeric sugars, amino acids and fatty acids) are utilized by the acidogenic or acid forming bacteria for their growth and accumulate volatile fatty acids such as acetic acid, propionic acid, butyric acid and valeric acid along with carbon dioxide, water and hydrogen, called acidogenesis. These bacteria are fast-growing with a doubling time of about 30 min. The accumulation of volatile fatty acids can be written as [15]:

$$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2 \quad (2)$$

$$C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O \quad (3)$$

The volatile fatty acids except acetic acid such as propionic acid, butyric acid and valeric acid are again utilized by acetogenic bacteria for their growth and form acetic acid and hydrogen, called acetogenesis. These bacteria grow slowly with a doubling time of 1.5 to 4 days. The acetogenesis reaction can be written as [15]:

$$CH_3CH_2COOH + 2H_2O \leftrightarrow CH_3COOH + CO_2 + 3H_2 \quad (4)$$

Finally, methanogens utilize acetic acid, hydrogen and carbon dioxide and form methane gas, called methanogenesis. The

methane is produced from a number of simple substances: acetic acid, ethanol, methanol or carbon dioxide and hydrogen. Methanogens, which utilize acetic acid known as acetoclastic methanogenesis whereas hydrogen and carbon dioxide utilizing methanogens are known as hydrogenotrophic methanogenesis. The methanogens also grow slowly with a doubling time of 2 to 4 days. Madigan et al. [15] found stoichiometrically that about 70% of the methane is produced via the acetate pathway. The methanogenesis reactions can be written as [15]:

$$2CH_3CH_2OH + CO_2 \leftrightarrow 2CH_3COOH + CH_4 \tag{5}$$

$$CH_3COOH + CO_2 \leftrightarrow CH_4 + 2CO_2 \tag{6}$$

$$CH_3OH + H_2 \leftrightarrow CH_4 + H_2O \tag{7}$$

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \tag{8}$$

Biogas formation is governed by the specificity of the microorganisms and the metabolic regulations which are dependent on the process parameters. Hence, the monitoring of the growth of microbial cells and methane formation, and the cell behavior towards the substrate and the product, particularly on their concentration, need careful studies. A functional relationship between specific growth rate (μ) and the rate limiting substrate concentration (S) is generally expressed by Monod-type equation [16]:

$$\mu = \frac{\mu_m S}{K_S + S} \tag{9}$$

where μ_m is the maximum specific growth rate, and K_S is the value of the rate limiting substrate concentration at which the specific growth rate is half of its maximum value, generally referred to as the saturation constant.

In most of the processes, high concentrations of substrate and/or product often lead to inhibitory effects. Anaerobic digestion generally experiences inhibition to growth of cells from the substrate and acid (product/substrate). The inhibition can be categorized into three sections: A. substrate inhibition; B. product inhibition; C. both substrate as well as product inhibition. As the acid formation increases, the acid inhibits the growth of acidogens, acetogens and methanogens. The acid formation is a product for acidogens, substrate and product for acetogens and substrate for methanogens. Several inhibition models have been proposed by various researchers for either substrate or product or both. Therefore, Monod-type equation can be modified for substrate and/or product inhibition as [16,17]:

2.1. Acidogens

$$\mu_a = \frac{\mu_{ma} S_a}{(K_{Sa} + S_a)\ (1 + (P_a/K_{Pa}))} \tag{10}$$

where μ_a is the specific growth rate of acidogens; μ_{ma} is the maximum specific growth rate of acidogens, S_a is the substrate concentration for acidogens, P_a is the volatile fatty acid concentration, K_{Sa} and K_{Pa} are the saturation and product inhibition constants, respectively.

2.2. Acetogens

$$\mu_{ac} = \frac{\mu_{mac} S_{ac}}{(K_{Sac} + S_{ac})\ (1 + (S_{ac}/K_{Iac}))\ (1 + (P_{ac}/K_{Pac}))} \tag{11}$$

where, μ_{ac} is the specific growth rate of acetogens; μ_{mac} is the maximum specific growth rate of acetogens, S_{ac} is the substrate concentration (volatile fatty acids except acetic acid) for acetogens, P_{ac} is the product (acetic acid) concentration, K_{Sac}, K_{Iac} and K_{Pac} are the saturation, substrate inhibition and product inhibition constants, respectively.

2.3. Methanogenesis

$$\mu_m = \frac{\mu_{mm} S_m}{(K_{Sm} + S_m)\ (1 + (S_m/K_{Im}))} \tag{12}$$

where, μ_m is the specific growth rate of methanogens; μ_{mm} is the maximum specific growth rate of methanogens, S_m is the substrate concentration (acetic acid) for methanogens, P_m is the product (methane) concentration; K_{Sm} and K_{Im} are the saturation and substrate inhibition constants, respectively.

The methane formation is an anaerobic process, the dissolved oxygen is not considered as a limiting substrate of the system. Therefore, the proposed kinetics can be modified in terms of both, the substrate and the product and combined with death rate and cell maintenance. The rate of cell mass formation, product formation and substrate consumption are related to the cell concentration (X), product concentration (P) and substrate concentration (S) as follows [18]:

$$\frac{dX}{dt} = \mu X - K_d X \tag{13}$$

$$\frac{dP}{dt} = Y_{P/X} \frac{dX}{dt} \tag{14}$$

$$-\frac{dS}{dt} = \frac{1}{Y_{X/S}} \left(\frac{dX}{dt}\right) + \frac{1}{Y_{P/S}} \left(\frac{dP}{dt}\right) + K_{CM} X \tag{15}$$

or,

$$-\frac{dS}{dt} = \frac{1}{Y_{X/S}} \left(\frac{dX}{dt}\right) + \frac{Y_{P/X}}{Y_{P/S}} \left(\frac{dX}{dt}\right) + K_{CM} X \tag{16}$$

or,

$$-\frac{dS}{dt} = \left(\frac{1}{Y_{X/S}} + \frac{Y_{P/X}}{Y_{P/S}}\right) (\mu - K_d + K_{CM}) X \tag{17}$$

where K_d is the specific death rate (h^{-1}); K_{CM} is the maintenance coefficient (h^{-1}); $Y_{X/S}$, $Y_{P/X}$ and $Y_{P/S}$ are the yield coefficients for cells formation, product formation per unit cell mass and product formation per unit substrate consumed, ($g\ g^{-1}$), respectively.

DAD process, basic theme of article, follows the same sequential steps in production mechanism like wet anaerobic digestion process. It exhibited a poor startup performance in the first step (hydrolysis) due to presence of small quantities of water [19,20]. Volatile fatty acids (VFAs), alcohols, CO_2 and H_2 are the major products from monomeric compounds of raw waste. VFA act as intermediate compounds, treated as an indicator of the digestion efficiency, but high concentration of these acids will result in decrease of pH, inhibition of acidification destruction and ultimately failure of digester [21]. The overall reaction is shown in equation as below:

$$\text{Organic Matter} \rightarrow CH_4 + CO_2 + H_2 + NH_3 + H_2S \tag{18}$$

In DAD process, the undiluted substrate is pretreated and fed into the air tight digester under strict anaerobic conditions. This process produces lower amount of stabilized sludge (3–20 times lower than aerobic process) since the energy yield of microorganism in DAD is relatively low [22]. Most of the energy derived from the substrate breakdown is found in the final product as methane (CH_4). Methanogens, the important methane producers are directly co-related with organic loading rate, volatile solids removal and methane production [23–27]. The basic and main reactions in DAD process have been explained in Fig. 1.

3. Basic fundamental aspects

A wide variety of systems has been developed to treat various types of organic wastes in anaerobic condition. These systems can

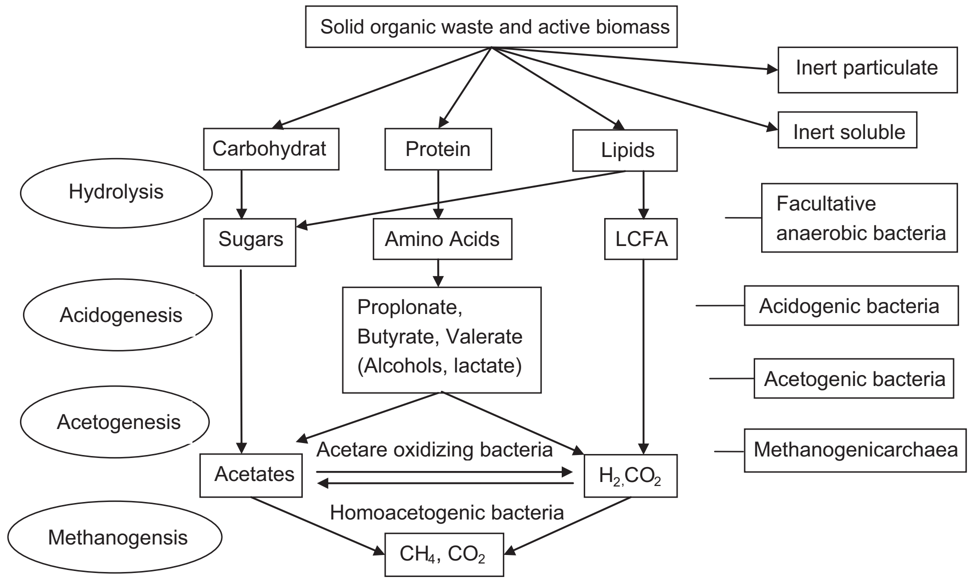

Fig. 1. Main steps and pathways of DAD process [25].

Table 1
System basics according to variation in processes of anaerobic digestion [23].

System	System basics
1. According to total solid	
(a) Wet process	The organic feedstock is slurried with large amount of water to provide a dilute feedstock of 10–15% dry solids
(b) Dry process	The organic feedstock used a dry solids content of 20–40%
2. According to digester feed	
(a) Batch-process	The reactor vessels are loaded with raw feed-stocks and inoculated with digestate from another reactor. They are then sealed and left until thorough digestion has occurred. The digester is then emptied and a new batch of organic mixture is added
(b) Continuous process	The reactor vessel is fed continuously with digested materials and fully degraded materials are continuously removed from the bottom of the reactor
3. According to steps involved	
(a) Single steps	All digestion steps occurred in one digester
(b) Multi-steps	Process consists of several reactors, often the organic acid forming stage of the anaerobic digestion process (acetogenesis) is separated from the methane forming stage (methanogenesis)
4. According to feedstock used	
(a) Co-digestion	The organic material is mixed with some other substrates (like food waste with animal manure). This improves the digestion process by maintaining C/N ratio so the gas production improves

All these system work on the same mechanism as those of the basic steps of the reaction in anaerobic conditions.

be categorized according to the variations in the process as described in Table 1 and Fig. 2, respectively.

3.1. Microbial communities

The microbial communities in an anaerobic digestion process have an important role. Basically, three groups of microbial communities are responsible for anaerobic digestion. First group of organisms is responsible for hydrolyzing organic polymers and lipids to basic structural building blocks such as fatty acids, monosaccharide, amino acids, and related compounds. Second group of anaerobic bacteria ferments the breakdown products from the first group to simple organic acids, the most common of which is acetic acid. Second group of microorganisms, described as non-methanogenic, consists of facultative and obligate anaerobic bacteria that are often identified in the literature as “acidogens” or “acid formers”. Third group of microorganisms converts the hydrogen and acetic acid formed by the acid formers to methane gas and carbon dioxide [28]. The bacteria responsible for this conversion is strict anaerobes, called methanogenic, and are identified in the literature as “methanogens” or “methane formers”. Many methanogenic organisms identified in landfills and anaerobic digesters are similar to those found in the stomachs of ruminant animals and in organic sediments of lakes and rivers. The most important bacteria of the methanogenic group are the ones that utilize hydrogen and acetic acid. They have very slow growth rates; as a result, their metabolism is usually considered rate-limiting in the anaerobic treatment of an organic waste. Waste stabilization in anaerobic digestion is accomplished when methane and carbon dioxide are produced. Methane gas is highly insoluble, and its departure from a landfill or solution represents actual waste stabilization [28].

Under standard redox potential conditions, whereby acetogens and methanogens compete for substrates and the reductive synthesis of acetate from CO_2 by acetogenesis is thermodynamically less favorable than methanogenesis. Therefore, it has been found that the acetogens are capable of a highly diverse range of metabolic transformations [29]. In general, the optimal conditions for anaerobic

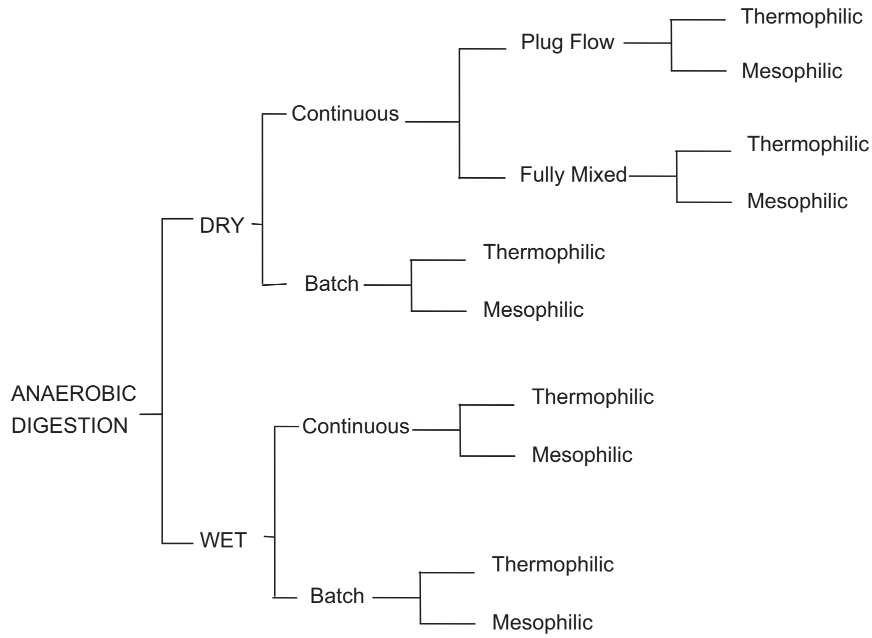

Fig. 2. Anaerobic digestion process according to operational parameters [23].

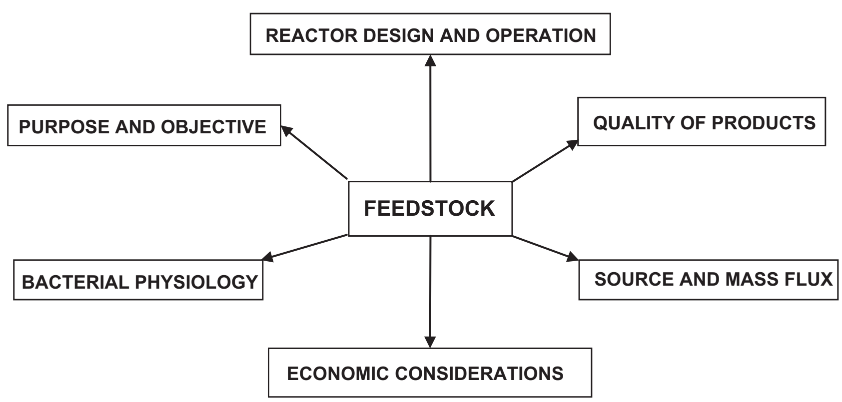

Fig. 3. Choice of feedstock influenced by various interrelated factors of process [44].

digestion of organic matter are near-neutral pH, constant temperature, mesophilic (30–40 °C) or thermophilic (50–60 °C), and a relatively consistent feeding rate. However, the micro-organisms themselves are adapted to relatively narrow temperature ranges. DAD requires attention to the nutritional needs of the bacteria to degrade the waste substrates. Imbalances among the different microorganisms can develop, if conditions are not maintained near optimum. The most important nutrients for bacteria are carbon and nitrogen, but these two elements must be provided in the proper ratio. Otherwise, ammonia can form up to levels that can inhibit the microorganisms. The appropriate carbon/nitrogen (C/N) ratio depends on the digestibility of the carbon and nitrogen sources. The most common result of imbalance is the formation of organic acids, which suppresses the methanogenic organisms. Acid formation is usually controlled naturally by inherent chemical buffers and by the methanogens themselves as they consume acids to produce methane. These natural controls can break down, if too much feed is added or organic acids are produced faster than they are consumed or inhibitory compounds accumulate, or the feed stream lacks natural pH buffers such as carbonate and ammonium. Solid concentrations higher than about 40% TS can also result in process inhibition, likely due to the reduced contact area available for the microorganisms. A wide variety of species involved in the process have been reported in literature [28–32].

Organic materials are most likely decomposed by heterotrophic microorganisms [33]. *Clostridium* species are most common among the degraders under anaerobic condition [34]. However, it is very unusual for a biological treatment to rely solely on a single microbial strain and generally a microbial consortium is responsible for the anaerobic digestion process [35]. Methanogens play an important role in the production of biogas [36]. All known methanogens express the methyl coenzyme M reductase (MCR) that catalyzes the terminal step in methane production during the anaerobic fermentation of biomass [37]. Methanogenic archaea (methanogens) group of strictly anaerobic Euryarch-aeota that convert H_2/CO_2, formate, methanol, methylamines and/or acetate to methane, and they are widely distributed in anoxic environments such as fresh water sediments, paddy fields, landfills sand intestinal tracts of ruminants and termites [38]. The heterogeneous nature of the substrate in DAD systems might create a multiplicity of ideal micro-environments for the growth of each of the microbial families required to complete the process. Thus, fermentation processes that are well understood in conventional submerged culture, behave quite differently in solid condition [39].

The characterization of the methanogenic microbial community is two-phase leach-bed biogas reactor system operated with plant biomass and the mesophilic-operated digestion system was found to be a well-suited method for the methanization of triticale silage [40]. The methanogenic archaea diversity of a biogas reactor supplied with swine feces as sole substrate under mesophilic conditions was investigated [41]. In this study, they found that methanobacterial instead of methanomicrobial are the most predominant methanogenic archaea in the biogas reactor fed with swine feces as sole substrate. A group of microorganisms such as actinomyces, *Thermomonospora*, *Ralstonia* and *Shewanella* are involved in the degradation of food waste into volatile fatty acids, whereas *Methanosarcina* and *Methanobrevibacter/ Methanobacterium* mainly contribute in methane production [42]. High concentration of organic acid like acetic acid (> 5000 mg/L) and butyric acid (> 3000 mg/L) in the biodigester has been found to inhibit the growth of microorganisms [43].

3.2. Feedstock

This section covers the main issues relating to feedstock for anaerobic digestion, including choice of feedstock, maintaining quantity and quality. The nature and potential sources of feedstock in an interaction with other parameters are also covered. Fig. 3 illustrates the influence of various interrelated process factors on feedstock choice. Anaerobic digestion is capable of recovering renewable energy from a wide range of feedstock. The feedstock needs to be: (i) biodegradable – as is the case for most organic matter; (ii) non woody – feedstock with a high proportion of lignocellulosic material (iii) balanced in macro and micro nutrients – as is the case for most waste derived organic matter. Therefore, feedstock can range from readily degradable wastewater to complex high-solid waste. Even toxic compounds may be degraded anaerobically depending on the technology applied. One important requirement is that a particular waste/wastewater containing a substantial amount of organic matter should finally be converted into main products such as, methane and CO_2. Fig. 4 shows the sources of eligible feedstocks available on this earth. Fig. 5 shows an overview of the various feedstocks assigned to the different eligible sources [44].

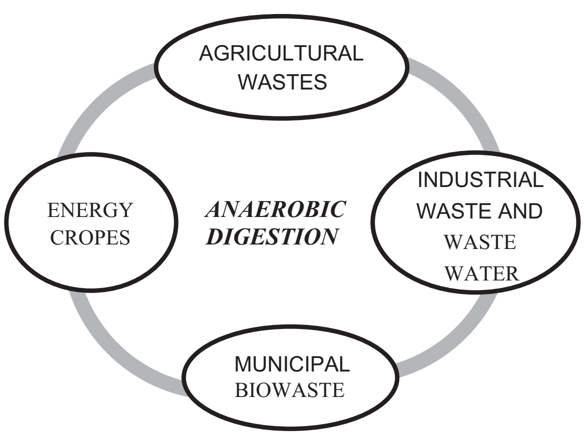

Fig. 4. Sources of eligible feedstock for anaerobic digestion [44].

In general, animal manure, sewage sludge, and food waste [45] are generally treated by liquid/wet AD, while organic fractions of municipal solid waste (OFMSW) [46] and lignocellulosic biomass such as crop residues and energy crops can be processed through solid substrate/dry AD. Agriculture accounts for the largest potential feedstock and most current applications. It mainly includes agro-industrial wastes, namely animal farm wastes, agricultural wastes and industrial wastes associated with agriculture and food production. Table 2 is showing the characteristics and operational parameters of the most important agricultural feedstocks [47].

Most of the agriculture wastes/crop residues rich in carbohydrate, which exist mostly as the polysaccharides cellulose and hemicelluloses, are not readily available for immediate fermentation. Cellulose, hemicelluloses, and lignin are covalently linked with each other which protect the potentially available carbohydrates from degradation. Therefore, pretreatment is required for the utilization of carbohydrates in lignocellulosic biomass [48,49]. Over the years, a number of different methods, including dilute acid [50], steam explosion [51], lime [52] and ammonia [53,54] have been developed for the pretreatment of lignocellulosic biomass. The main purpose of pretreatment is to remove or decrease the crystallinity of cellulose, and increase the surface area for microbial action [55].

Liew et al. [56] worked on the methane production from fallen leaves as a feedstock through simultaneous alkali treatment in DAD. They found that sodium hydroxide (NaOH) plays very important role in the delignification of lignocellulosic biomass and also by increasing the alkalinity the buffering capacity of DAD increases. The methane yield was found to be highest i.e. 82 L/kg volatile solids (VS) at NaOH loading of 3.5% and substrate-to-inoculum (S/I) ratio of 4:1. However, at S/I ratio of 6:2 with NaOH loading of 3.5% methane yield could be increased and was found to be the maximum. Also, reduction of about 35% in biogas yield was found at S/I ratio of 6:2 and NaOH loading of 3.5% when the TS content increases from 20% to 26%. Teater et al. [57] studied the most suitable pretreatment conditions to convert AD fiber into ethanol by an alkali pretreatment of AD fiber. The main objective of the study was to compare the suitability of AD fiber from a

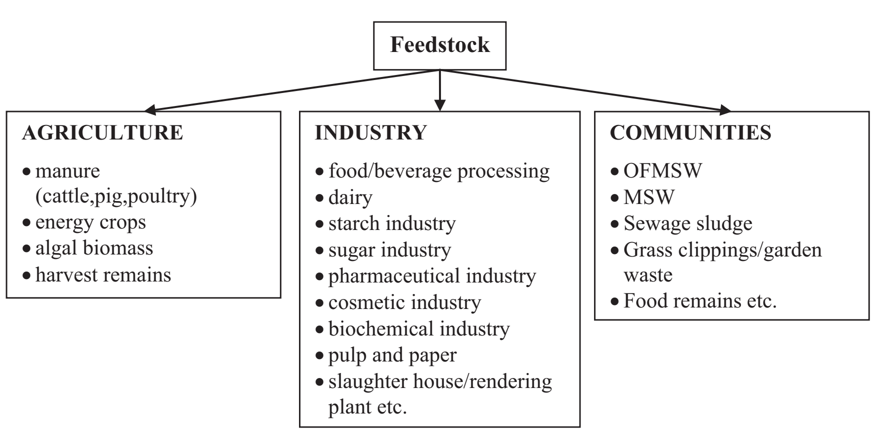

Fig. 5. Categorization of various feedstocks from different sources [47].

Table 2
Characteristics and operational parameters of important agricultural feedstock [47].

Feedstock	Total solids TS (%)	Volatile solids (% of TS)	C:N ratio	Biogas yield ($m^3\ kg^{-1}$ VS)[c]	Retention time (d)	CH_4 content	Unwanted substances	Inhibiting sunstances	Frequent problems
Pig slurry	3–8[d]	70–80	3–10	0.25–0.50	20–40	70–80	Wood shavings, bristles, H_2O, sand, cords, straw	Antibiotics, disinfectants	Scum layers, sediments
Cow slurry	5–12[d]	75–85	6–20[a]	0.20–0.30	20–30	55–75	Bristles, soil, H_2O, NH_4^+, straw, wood	Antibiotics, disinfectants	Scum layers, poor biogas yield
Chicken slurry	10–30[d]	70–80	3–10	0.35–0.60	>30	60–80	NH_4^+, grit, sand, feathers	Antibiotics, disinfectants	NH_4^+-inhibition, scum layers
Whey	1–5	n.a.	80–95	0.80–0.95	3–10	60–80	Transportation impurities		pH-reduction
Ferment. slops	1–5	80–95	4–10	0.35–0.55	3–10	55–75	Undegradable fruit remains		High acid conc., VFA-inhibition
Leaves	80	90	30–80	0.10–0.30[b]	8–20	n.a.	Soil	Pesticides	
Wood shavings	80	95	511	n.a.	n.a.	n.a.	Unwanted material		Mechanical problems
Straw	70	90	90	0.35–0.45[e]	10–50[e]	n.a.	Sand, grit		Scum layers, poor digestion
Wood wastes	60–70	99.6	723	n.a.	∞	n.a.	Unwanted material		Poor anaerobic biodegradation
Garden wastes	60–70	90	100–150	0.20–0.50	8–30	n.a.	Soil, cellulosic component	Pesticides	Poor innoculu. of cellulosic comp.
Grass	20–25	90	12–25	0.55	10	n.a.	Grit	Pesticides	pH-reduction
Grass silage	15–25	90	10–25	0.56	10	n.a.	Grit		pH-reduction
Fruit wastes	15–20	75	35	0.25–0.50	8–20	n.a.	Undegradable fruit remains,	grit Pesticides	pH-reduction
Food remains	10	80	n.a.	0.50–0.60	10–20	70–80	Bones, plastic material	Disinfectants	Sediments, mechanical problems

n.a. – not available.

[a] Depending on straw addition.
[b] Depending on drying rate.
[c] Depending on retention time.
[d] Depending on dilution.
[e] Depending on particle size.

completely stirred tank reactor (CSTR) for ethanol production from switchgrass and corn stover. The cellulose utilization efficiencies determined in the study showed that AD fiber with CSTR was a more suitable biorefining feedstock compared to the switch grass and corn stover.

Chanakya et al. [58] optimized the design parameters for DAD using six different types of commonly available fresh and dry feedstocks for their decomposition pattern and methanogenic activities. They suggested to use the mixed biomass feed-stock comprising of fresh and dry biomass for stable biogas production with high conversion efficiency and yield. Dry anaerobic fermentation of energy crops from agriculture sector also offers some attractive advantages in DAD process. But, after extensive literature search, little information was found, which needs further research and development. However, currently energy crops for anaerobic digestion have not reached at the significant findings. In some cases, investigations have been reported using pretreated plant biomass (i.e. silage) for anaerobic digestion in farm digesters. On the other hand, feedstocks from community category such as food waste (FW) and organic fractions of municipal solid waste (OFMSW) are also important for the DAD process. Kim and Oh [59] compared two different dry anaerobic co-digestion systems on different mixtures of OSW under mesophilic conditions; a schematic of the DAD system is given in Fig. 6. Reactor I was fed with food waste (FW) and paper waste (PW); the maximum treatability was found to be at hydraulic retention time (HRT) of 40 d and solid content of 40% TS. The biogas production rate (BPR), CH_4 production yield (MPY) and VS reduction achieved in this condition were found to be 5.0 $m^3/m^3/d$, 0.25 m^3 CH_4/g COD added, and 80%, respectively.

Reactor II was fed with FW and livestock waste (LW), and LW content was increased during the operation. Until a 40% LW content increase, reactor II exhibited a stable performance. A BPR of 1.7 $m^3/m^3/d$, MPY of 0.26 m^3 CH_4/g COD added, and VS reduction of 72% were achieved at 40% LW content.

According to the US EPA survey, 2002, United States-Americans throw away about 43.6 million tons of food each year and it includes uneaten food and food preparation leftovers from residences, commercial establishments such as restaurants, institutional sources like school cafeterias, and industrial sources like factory lunchrooms [60]. Similarly, according to a report published by California Integrated Waste Management Board, the amount of food waste generated in California was estimated to be 5.6 million wet tons per year or 2.2 million dry tons per year in 1999 [61,62].

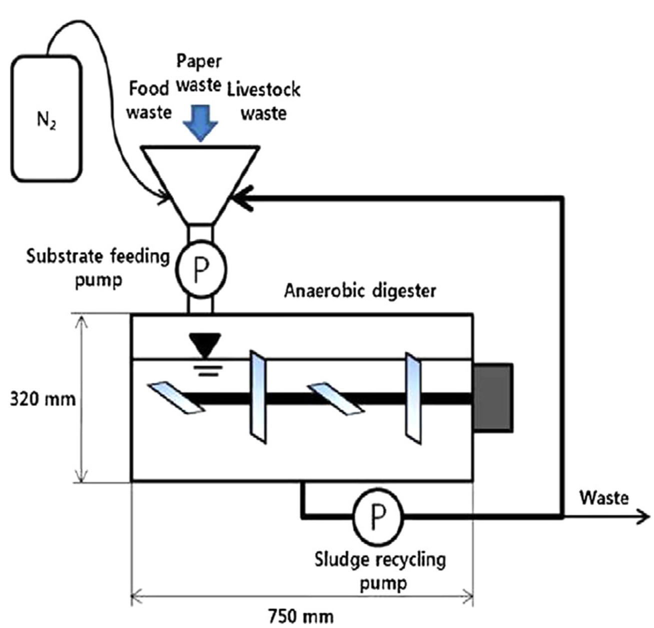

Fig. 6. Schematic of anaerobic dry digestion system [59].

Table 3
Biogas production and energy output potential per ton of fresh feedstocks [64].

Feedstock	Number of animals to produce 1 t/d	Dry matter content (%)	Biogas yield (m^3/t feed-stock)[a]	Energy value (MJ/m^3 biogas)[d]
Cattle dung[b]	20–40	12	25	23–25
Pig slurry	250–300	9	26	21–25
Laying hen litter[c]	8000–9000	30	90–150	23–27
Broiler manure	10,000–15,000	60	50–100	21–23
Food processing waste	–	15	46	21–25

[a] Indicative values have been taken.
[b] Cattle slurry covers both dairy and beef cattle.
[c] Poultry manures are highly susceptible for ageing and should be used as fresh as possible.
[d] 1 m^3 of biogas (at an assumed 20 MJ/m^3) would give the following:

- electricity only – 1.7 kWh of electricity (assumed conversion efficiency 30%),
- heat only – 2.5 kWh of heat (assumed conversion efficiency 70%),
- combined heat and power – 1.7 kWh of electricity and 2 kWh of heat.

Zhang et al. [63] studied the foodwaste characterstics for assessing their potential as a feedstock for a thermophilic anaerobic digester and to determine the overall variability and consistency of this material over time. They analyzed the nutrient contents of food waste that was found to be suitable for anaerobic digestion. On average, food waste had C/N ratio of 14.8. The results of the anaerobic digestion tests showed that food waste had average methane yields of 435 mL/g VS after 28 days of digestion at 50 ± 2 °C. About 80% of the methane yield was obtained after the first 10 days of digestion, giving a methane yield of 348 mL/g VS. The methane accounted for 73% of the biogas produced. Lissens et al. [64] studied the co-digestion of 70% food waste, 20% fecal matter, and 10% green algae at 39 °C, and a biogas yield of up to 90% was obtained. In the year 2008, in South Korea, the generation of FW increased and reached 15,142 t/d, which accounts for 40.7% of total MSW. Singh et al. [26] studied the possibilities of energy generation from MSW in Indian context with special references to the current technologies. Different feedstocks produce different amounts of gas: 1 t of cattle manure will not produce the same as that by 1 t of chicken manure. The gas production performances of different feedstocks are given in Table 3.

Different feedstocks require different loading systems, depending on the consistency of the feedstock (i.e. type of waste). Hence, pre-treatments and co-digestion such as separation of non-degradable materials (e.g bricks, sand, grit and long straw), adding of water, or removal of water have been suggested in the literature [45]. In general, it is not advisable to add water as more energy would be required for the processing of diluted feedstock. However, water may be required for conditioning of waste, homogeneity of material and stirring of material. During the last decade, numerous non-agricultural organic wastes have been introduced for harvesting through co-digestion. The feedstocks derived mainly from agro- and food industries as well as from municipalities (biogenic wastes) are easily available for co-digestion. The quality of the feedstock in terms of its gas yield partially depends on its freshness. An acidic feedstock may inhibit microbial activity in the digester. Ideally, the pH range in the digester should be 6.8–8. Moreover, the feedstock also dictates the quality of the products such as biogas, digested sludge and the necessity of effluent

post-treatment at the end of the digestion process. Since the final products of the anaerobic digestion are further processed to thermal and electrical energy (biogas) and soil conditioners (digested sludge), a comprehensive assessment of the composition and purity of the feedstock is required [47].

4. Process parameters

The formation of methane is influenced by a number of parameters, such as temperature, type of feedstock, pH level, retention time, C/N ratio, etc. The maximum production takes place when these parameters are chosen in the optimum range. The optimized range of some of these parameters is discussed in this section.

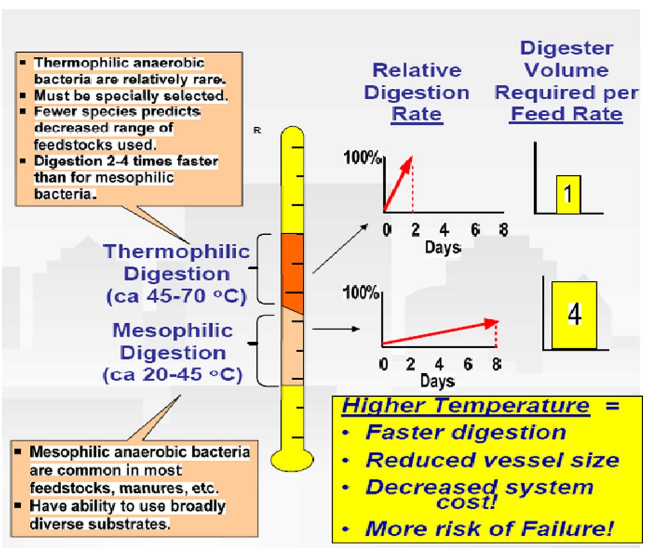

Fig. 7. Process efficiency relation with temperature variation [69].

4.1. Temperature

The formation of methane occurs over a broad range of temperatures from low temperature, e.g. sewage in the arctic, to high temperature over 100 °C. Three different temperature ranges for methane formation [65] have been defined on the basis of microbial activity as given below:

- psychrophilic temperature (or cryophilic) from 10 to 20 °C;
- mesophilic temperature from 20 to 45 °C, usually 35 °C;
- thermophilic temperature from 50 to 65 °C, usually 55 °C.

Psychrophilic digesters were more popular than others in late 1980s when the biogas was used for heating purposes. At 23 °C, the net heat production was higher than that of mesophilic digesters [66]. However, no anaerobic psychrophilic bacteria have been found at temperature below 20 °C. Nowadays, mesophilic digesters are the most popular; however, thermophilic conditions are applied in most of the large-scale centralized biogas co-digesters. Depending on the feedstock composition and the type of reactor, optimum temperature of digestion varies; however it should be maintained at an approximately constant level for maximum gas production rate. In the literature [67,68], a number of mesophilic and thermophilic anaerobic bacteria are described i.e. in the temperature range between 28 °C and 42 °C and between 55 °C and 72 °C, respectively (Fig. 7). It has been found that the thermophilic digesters have lower retention time, which is due to high catalytic activity of thermophiles [67]. Thermophiles also provide the added benefit in terms of low contamination.

The effect of six different inoculum sources on anaerobic thermophilic digestion of separately collected organic fraction of municipal solid wastes (SCOFMSW) was studied by Forster-Carneiro et al. [69]. In the study, sludge was found to be the most appropriate inoculum source for anaerobic thermophilic digestion of the treatment of OFMSW under dry conditions (30% TS) at 55 °C and cattle was found to be the worst inoculum source with respect to methane yield and organic matter removal. Mashad et al. [70]

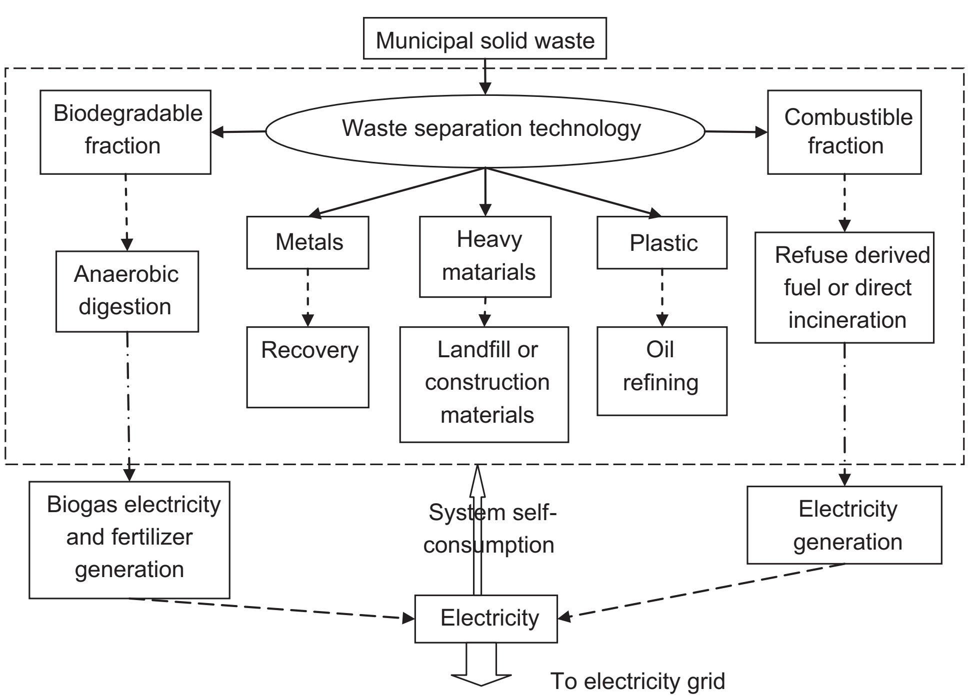

Fig. 8. Proposed MSW treatment based on water separation technology [74].

studied the effect of temperature variations on the anaerobic digestion of cattle manure and found that the biogas yield of anaerobic digestion of OFMSW under thermophilic conditions is much higher than that from mesophilic conditions.

Zeemann et al. [71] adapted the mesophilic bacteria to lower or higher temperatures and found that there is slow adaptation of mesophilic bacteria to lower temperatures. The change from mesophilic to thermophilic temperatures or vice versa is very common in animal waste digesters. However, in case of mesophiles it might take months of time to be adapted for psychrophilic temperatures [72]. From the observations, it was also found that the gas production of mesophilic digestion is always greater than that of psychrophilic digestion by 30% for cattle manure [72] and 22% for sewage sludge. Fdez.-Güelfo et al. [73] carried out a number of experiments to find out the effect of solid retention time (SRT) by varying SRT from 8 to 40 days, for the anaerobic digestion of OFMSW under dry (30% TS) thermophilic (55 °C) conditions and found 15 days of optimum SRT.

Dong et al. [74] studied the feasibility of anaerobic digestion of water sorted organic fraction of municipal solid waste (WS-OFMSW). The proposed layout of the MSW treatment based on water separation technology has been illustrated in Fig. 8. Three wastes of different total solid contents (TS = 16.0%, 13.5% and 11.0%) were selected and digestion was carried out in a group of bench-scale (35 L) reactors at 30 ± 2 °C. In the study, it was found that the biodegradability of OFMSW was better than that of both WS-OFMSW and mechanically sorted OFMSW. However, WS-OFMSW with VS/TS of 61.6% was better than the mechanically sorted OFMSW. Shu-guang et al. [75] performed dry mesophilic and thermophilic digestions of organic solid waste for 6 weeks and found that the DAD under thermophilic conditions shows better start-up performance than that from the mesophilic conditions.

Hartmann and Ahring [76] applied different strategies of AD of OFMSW and found that the thermophilic process for treating OFMSW under DAD is a more reliable option than the mesophilic process. It also presents growth of pathogens. Hartmann and Ahring [77] also performed co-digestion of manure under DAD of OFMSW under thermophilic conditions and found a better option for digestion. Bolzonella et al. [78] studied thermophilic semi-dry anaerobic digestion of OFMSW in a pilot scale. They found that the environment in the reactor can be easily changed from mesophilic (37 °C) to thermophilic (55 °C) in a short time with interruption of feeding for a few days. The possibility of having a short start-up phase to reach the thermophilic conditions with a mesophilic inoculum has also been confirmed in industrial scale. Digestion of organic urban wastes using thermophilic and mesophilic processes has also been studied by researchers and they found that the thermophilic process is a more realistic and viable option [79–82]. The added amount of heat required for thermophilic operations can be offset by the higher gas production yields and rates [82].

4.2. Carbon to nitrogen ratio (C/N)

The C/N ratio represents the relationship between the amount of carbon and nitrogen in the organic materials. C/N ratio for suitable anaerobic digestion should be neither high nor low [83]. In case of a high C/N ratio the methanogens consume nitrogen rapidly, which results in lower gas yield. On the other hand a lower C/N ratio causes ammonia accumulation and pH values exceeding 8.5, which is toxic to methanogenic bacteria. According to Weiland [84], C/N ratio in the range of 20–30 is the best for a process with high gas yield. Parkin and Owen [82] and Pang et al. [85] also found optimum C/N ratios in AD between 20 and 30 with an optimal ratio of 25. However, optimal C/N ratio is a function of the type of feedstock and varies with type of feedstock. Optimum C/N ratio of the materials can be maintained by mixing materials of high and low C/N ratio; e.g. organic solid waste can be mixed with sewage or animal manure. However, C/N ratio ranging from 22 to 25 is the most suitable for anaerobic digestion of fruit and vegetable waste [86]. On the other hand, Romano and Zhang [87] suggested that the optimal C/N ratio of onion juice and digested sludge should be maintained at 15. Zhu and Li [88] studied DAD of organic wastes and found C/N ratio between 15 and 18, when corn stover was inoculated with digested sewage sludge. The digestion rate decreased when C/N ratio increased to 21 or higher due to decrease in pH in the first 7 d at 37 °C. Yen and Chiu [83] balanced high nitrogen concentration of algal sludge by using waste paper to the optimal C/N ratio for co-digestion between 20 and 25.

4.3. pH level

The pH value is a measurement of acid concentration in aqueous systems i.e. the concentration of hydrogen ions. Anaerobic bacteria, specially the methanogens, are sensitive to the acid concentration in the digester and their growth can be inhibited by acidic conditions. Many researchers have optimized the pH values for different stages of AD viz. hydrolysis, acidogenesis and methanogenesis. According to Huber et al. [89] and Yang and Okos [90], the optimum pH value for methanogenesis was found to be around 7.0. The pH values differ for each step during the digestion i.e. pH levels for processes of acidification and methanogenes are different for each step. Lee et al. [91] found the optimum range of pH for methanogenesis in AD to be 6.5–8.2. However, Kim et al. [92] reported the pH value at 5.5 and 6.5 respectively, for hydrolysis and acidogenesis. The pH of digestate varies with retention time. The initial step, acetogenesnis process in a batch reactor, occurs at a rapid pace. pH value goes below 5 in the acetogenesis process due to accumulation of large amounts of organic acids. Park et al. [93] studied different operational parameters in thermophilic acid fermentation of kitchen waste and found the optimum range of pH for thermophilic acidogens as 6–7. The methanogens are sensitive to acid condition; therefore excessive accumulation of acid should be avoided. According to Liu et al. [94], maximal biogas yield in anaerobic digestion is found to be in the pH range of 6.5–7.5. However, pH reduction can be controlled by adding lime or recycled filtrate obtained during residue treatment. Increase in concentration of ammonia in the digestate increases the pH value above 8 and indicates the methanogenesis stage of digestion. Agdag and Sponza [95] reported a very narrow range of suitable pH (7.0–7.2) in the industrial sludge during the last 50 days of anaerobic incubation. Similarly, Ward et al. [96] found that the suitable range of pH for AD was 6.8–7.2.

4.4. Retention time

The retention time (RT) is defined as time required for the complete degradation of the organic matter or it may be defined as the average time the organic matter remains in a digester. It is defined by

$$RT = \text{liquid volume}/\text{daily flow} \tag{19}$$

The RT for completion of the anaerobic digestion reactions varies with process parameters such as temperature and waste composition. The RT for biomass digestion in mesophilic condition varies from 10 to 40 days. However, RT in thermophilc condition is found to be lower. A high solids reactor operating in the thermophilic range has a retention time of 14 days. RT is directly proportional to the degradation rate; lower the degradation rate, higher the RT [97]. Schaefer [98] and Schaefer and Sung [99] have studied a thin corn stillage (94 g TCOD/L and 61 g TS/L) in a completely mixed thermophilic digester at different hydraulic

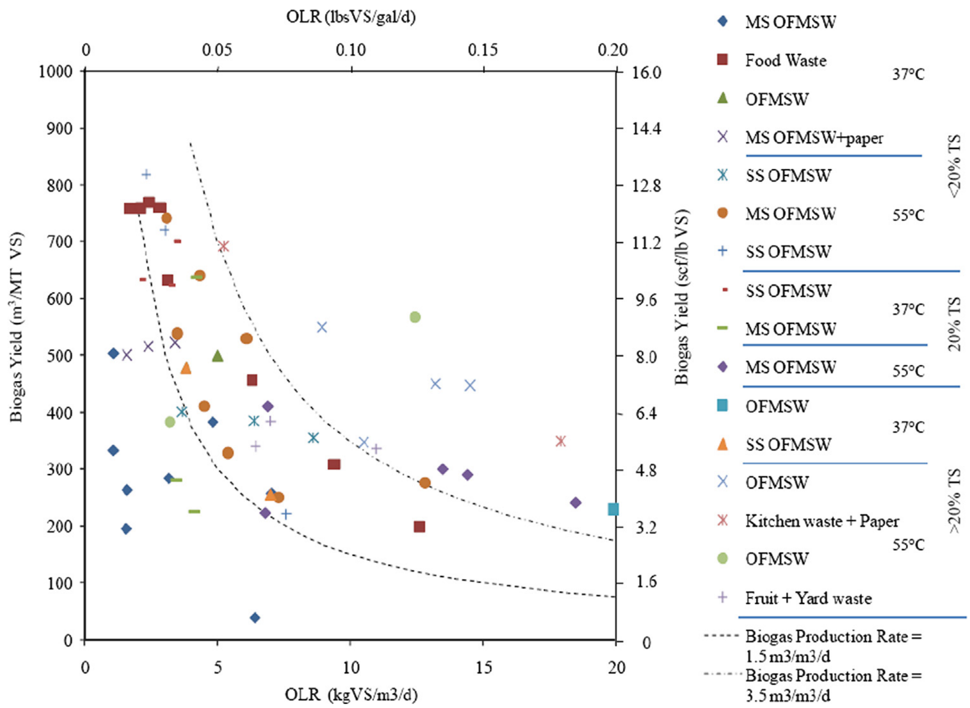

Fig. 9. Biogas yield as a function of organic loading rate [76].

Table 4
Comparison of process weaknesses and strengths of various reactors [104].

System		Strengths	Weaknesses
One stage versus two stages digesters	One stage	Simpler design, less technical failure, low cost Efficient substrate degradation owing to recirculation of digestate	Higher retention time Foam and scum formation
	Two stages	Constant feeding rate to second stage, more robust process Less susceptible to failure	Complex and expensive to build and maintain Solid particles need to be removed from second stage
Dry versus wet Digesters	Dry	Higher biomass retention Controlled feeding Simpler pretreatment Low parasitic energy demands	Complex handling of feedstock Mostly structured substrates are used Material handling and mixing are difficult
	Wet	Good operating history Degree of process control is higher	Scum formation High consumption of water and energy Short-circuiting Sensitive to shock loads.
Batch versus continuous digesters	Batch	No mixing, stirring or pumping, low input process and mechanical needs, cost-effective	Channeling and clogging Larger volume Lower biogas yield
	Continuous	Simplicity in design and operation Low capital costs	Rapid acidification Large VFA(volatile fatty acid) formation
High rate bio-reactors		Higher biomass retention Controlled feeding Lower investment cost No support material is needed	Large start up times Channeling at low feeding rates

retention times (HRTs) i.e. 30, 20, 15 and 12 days at different volumetric organic loadings rates (OLRs) of 3.2, 6.1, 6.4 and 7.6 g TCOD/L-day, respectively. Steady state was found to be at HRTs of 30, 20 and 15 days. However reactors were found to be inactive after a week of operation at HRT of 12 days with total volatile fatty acids (TVFAs) of 7 g/L. Pig manure contains high fat content whereas cattle manure contains comparably high cellulose and days hemi-cellulose contents. It is observed that the digestion of pig manure requires lower RT than that of cattle manure. Average RTs in mesophilic digestion were found to be 12–18 days for cattle manure, 18–36 days for cattle manure with straw bedding and 10–15 days for pig manure [97].

4.5. Organic loading rate

Organic loading rate (OLR) is defined as the capacity of AD system for the biological conversion or the feeding amount of organic material (expressed as COD or volatile solids (VS)) to the system daily per m^3 of digester volume. For agricultural digesters

it can be written as

$$OLR = \frac{\text{daily flow} \times \text{VS concentration}}{\text{liquid volume}} \quad (20)$$

Gas production in the digester depends on OLR. If feeding in the system is above the suitable OLR, the gas production may decrease. This may be due to accumulation of the inhibiting substances such as fatty acids in the digester slurry. Thus, OLR is a very important controlling parameter in continuous systems. Due to overloading many plants have faced system failures [98,99]. On the basis of solid content, AD system can be classified mainly into three catogories: low solids (LS) AD systems contain less than 15% TS; medium solids (MS) – about 15–20% TS; high solids (HS) processes – 20–40% TS range [100,101]. Fernandez et al. [102] optimized OLR for mesophilic systems and found the values to be 2.5–3.5 kg VS/m^3-day for cattle manure, 5.0–7.0 kg VS/m^3-day for cattle manure with co-substrates and 3.0–3.5 kg VS/m^3-day for pig manure. A large number of laboratory-, pilot-, and full scale studies for the average biogas yield at a given OLR are shown in Fig. 9 by Hartmann and Ahring [76].

5. Type of reactors

In this section the existing and emerging DAD systems for a variety of reactors used in laboratory and commercial level are reviewed. Reactors can be classified into following categories:

- single stage,
- multi-stage,
- batch and continuous process.

In the DAD process, batch and continuous reactors are generally used. Single stage process is traditional and a multi-stage process has been developed based on the separation of phases in the reactor. Both single and multi stage-processes can be conducted in batch or in continuous flow fermentation. The single stage and the multi-stage systems can be further categorized as follows [103]:

single stage

- single stage low solids (SSLS),
- single stage high solids (SSHS);

multi-stage

- multi-stage low solids (MSLS),
- multi-stage high solids (MSHS).

Content of solid in the reactor affects the reactor volume and treatment process. Due to low content of water in high solid (HS) systems they require a smaller reactor volume per unit of production but this is counterbalanced by the more expensive equipment like pumps, etc. required. It is found that HS reactors have high OLR and are more robust in nature. Low solid (LS) systems contain less than 10% of solid and large amount of water so that they require high reactor volume and expensive post-treatment technology. Weakness and strengths of different types of reactors are given in Table 4 [104]. The expensive post-treatment is due to dewatering required at the end of the digestion process. In the 1980s, it was found that, most of the AD plants were using low solids processes but during the last decade high solids processes have increased appreciably [102]. Different digester configurations for high solid content feedstock are compared in Table 5.

5.1. Single stage process

In single stage processes both acidogenic phase and methanogenic phase are used in one reactor. These could be LS or HS depending on the total solids content in a reactor. As discussed above single and multi-stage processes are of two kinds, but here

Table 5
Comparison of different reactor configurations for high solid content feedstock [104].

Criteria	One stage versus two stages digesters		Dry versus wet digesters		Batch versus continuous digesters		High-rate bio-reactors
	One-stage	Two-stage	Dry	Wet	Batch	Continuous	
Bio-gas production	Irregular and discontinuous	Higher and stable	Higher	Less and irregular	Irregular and discontinuous	Continuous	Continuous and higher
Solid content (%)	10–40	2–40	20–50	2–12	25–40	2–15	< 4–15
Cost	Less	More	Less	More	Less	More	More
Volatile solid destruction	Low–high	High	40–70%	40–75%	40–70%	40–75%	75–98%
HRT (d)	10–60	10–15	14–60	25–60	30–60	30–60	0.5–12
OLR (kg VS m^{-3} d^{-1})	0.7–15	10–15 for second stage	12–15	< 5	12–15	0.7–1.4	10–15

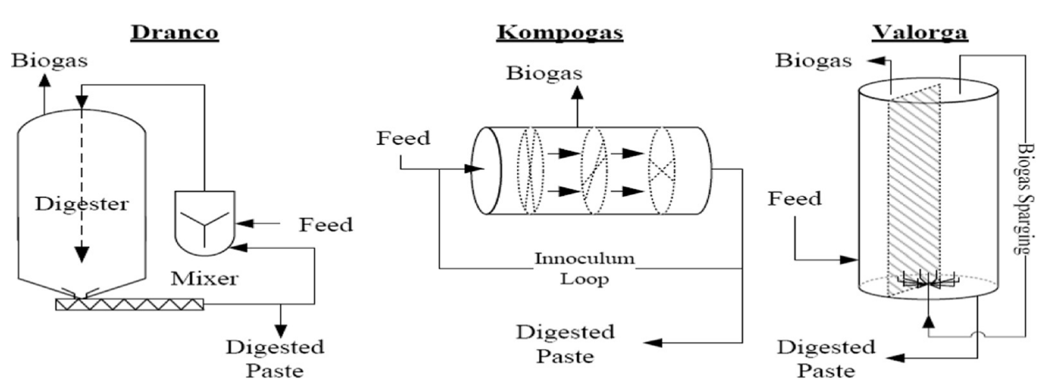

Fig. 10. Different types of SSHS reactor designs [104].

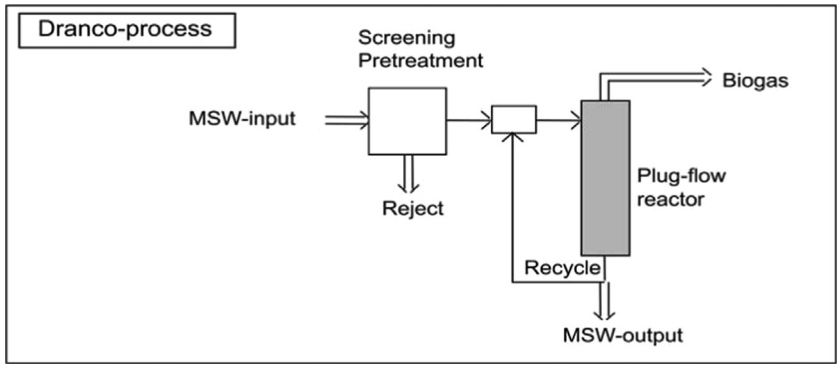

Fig. 11. Principle diagram of the Dranco process [107].

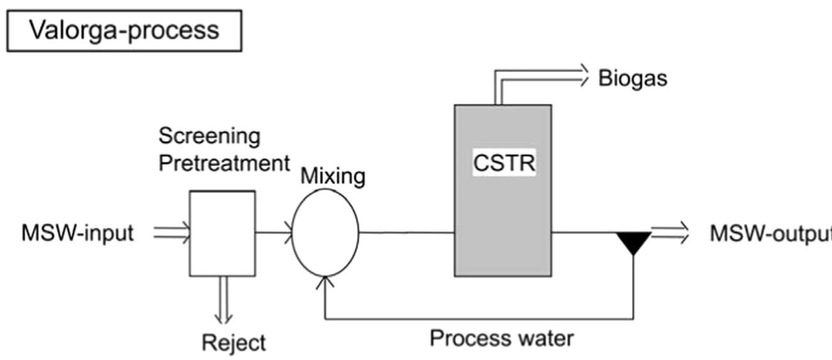

Fig. 12. Principle diagram of the Valorga process [107].

only high solid processes will be discussed as the paper deals with the DAD processes only.

5.1.1. Single-stage high solids (SSHS) process

Most of the research in HS systems was carried out during 1980s which resulted in higher biogas yield in undiluted waste. Untill 1980s most of the research was concentrated on LS systems and LS processes were well established and was in more use; however, from last few decades focus of research has been shifted from wet to dry systems. This is due to superiority of dry systems over wet systems; in some cases like pre-treatment, dry systems are less cumbersome than wet systems and have greater intolerance for impurities such as stones, glass or wood. Therefore in these systems only coarser impurities need to be moved out before digestion, e.g. >40 mm. Dry systems contain high solid contents which are in the range of 20–40%.

Due to the high solids content in dry systems they require different handling, mixing and pretreatment than those of wet systems. The main problem in the dry systems is the handling and transport of slurry. In wet systems, cheap instruments can be used for this purpose; however, for handling and transporting slurry for dry systems the instruments needed are expensive and robust. The feedstock is transported by conveyor belts, screws, and powerful pumps especially designed for highly viscous systems. Due to viscosity SSHS systems use plug-flow reactors; however, in SSLS complete mixing occurs. In plug-flow reactors contents are not completely mixed but move as a plug through the reactor from the feed port to the exit, like stuffing a sausage casing. This process requires heavy process equipment that can handle dry, viscous material that does not flow freely. Therefore, SSHS systems require no mechanical device within the reactor [105]. Most of the SSHS/DAD systems work in continuous process reactors, and function on the principle of adding waste to the reactor at regular intervals and removing an equal amount of finished product.

Over the last two decades, different types of SSHS for operating DAD systems have been in use in Europe; some of them are the Dranco, Kompogas, and Valorga processes, shown in Fig. 10. The biogas yield of above systems was reported to be in the range from 0.3 to 0.5 $m^3\ kg^{-1}$ volatile solids (VS). All the three reactors consist of a continuous single stage at mesophilic/thermophilic condition and the total solids content ranges from 20% to 40% [106].

The Dranco reactor was marketed by Organic Waste Systems (OWS) of Belgium; there are several Dranco plants in operation, such as, the one in Brecht, Belgium (12,000 t/a), Bassum, Germany (13,500 t/a), Kaiserslautern, Germany (20,000 t/a), and Salzburg, Austria (20,000 t/a) [107]. The Dranco (Dry Anaerobic Composting) process is a true dry-process for treatment of the organic fraction of MSW. In the DRANCO reactor, the feedstock is fed from the top and digested matter is collected from the bottom (Fig. 11). There is no internal mixing mechanism occuring in this process. Total solid content in this type of reactor varies from 30% to 40% [108]. In this process, mixing of material occurs outside the tank and recycled digestate with fresh feedstock is blended in the ratio of 6:1 before feeding to the tank from the top [109]. The Valorga process was developed in France and is a semi-dry, mesophilic process (Fig. 12). The Valorga process takes place in the following steps. In this process, mixing of waste with recycled process water is done after pretreatment. Process water is recycled to get the solid content at the level of 30% TS inside the reactor [102]. After that the influent is pumped into the reactor which is of a fully mixed reactor type. Mixing takes place by pneumatic stirring, i.e. the produced biogas is compressed and sent through the contents of the reactor [107].

There are several full-scale Valorga plants worldwide, such as in Grenoble, France (16,000 t/a), Amiens, France (85,000 t/a), Papeete, Tahiti (90,000 t/a), Tilburg, Netherlands (52,000 t/a) and Tamara in French Polynesia (92,000 t/a). The Kompogas process

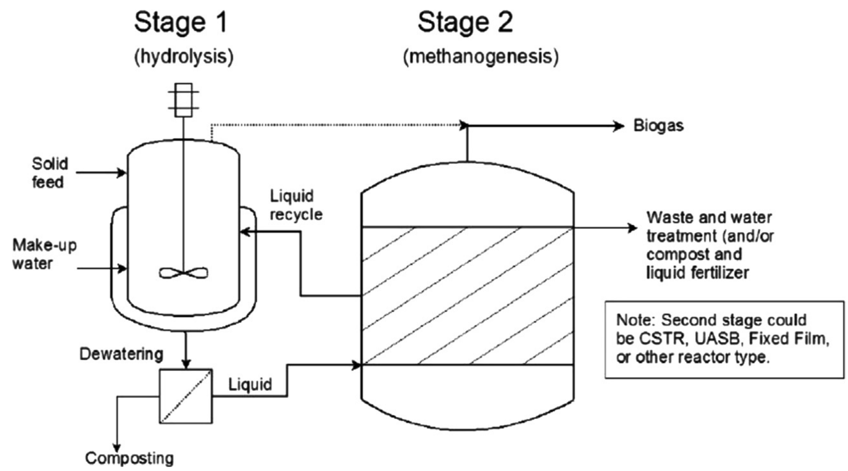

Fig. 13. Schematic of a two-stage anaerobic digestion system in general [110].

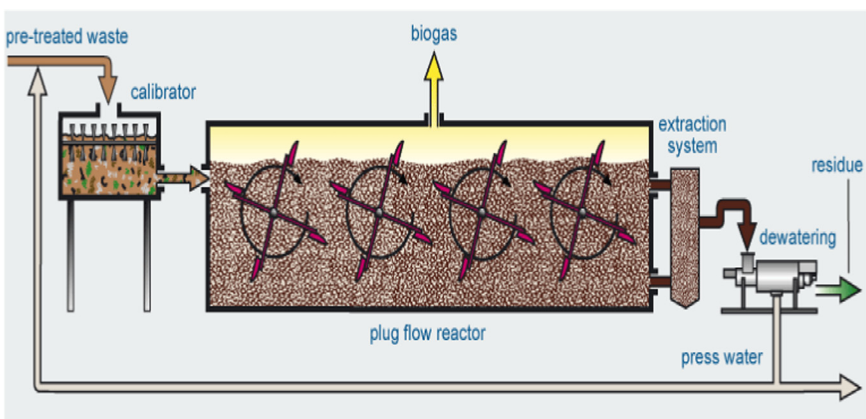

Fig. 14. Linde-KCA two-stage dry digester [112].

was developed by Schmid of Glattbrugg, Switzerland, in the 1980s. In Kompogas reactors the movement takes place in plug flow in a horizontally disposed cylindrical steel tank. Mixing is done by the use of an agitator which helps in carrying the material from the inlet to the outlet, keeping heavy solids in suspension, and degassing the thick digestate. Total solid content in this process is at about 23%. If TS content is below 23% the heavy materials such as sand and glass can accumulate at the bottom and higher TS content can obstruct the material flow [76].

5.2. Multi-stage process

As we know, in single stage processes only one reactor is used for both hydrolysis/liquefaction–acetogenesis and methanogenesis processes but multi-stage processes use separate reactors for the different stages of DAD to improve the digestion process. The concept behind the multi-stage systems is to separate the different phases of the AD process so that optimal conditions can be applied in each of them and overall rate can be increased [110]. The difference can be in the OLR of each stage, the presence or absence of oxygen, the introduction of an intermediate treatment, or the overall reactor configuration. Many different combinations of operating factors are possible.

This process uses basically two reactors, the first for hydrolysis/liquefaction–acetogenesis and the second for methanogenesis. Typically two-stage [111] processes attempt to optimize the hydrolysis and fermentative acidification reactions in the first stage, where the rate is limited by hydrolysis of complex carbohydrates. The second stage is optimized for methanogenesis, where the rate in this stage is limited by microbial growth kinetics. Since methanogenic archaea prefer pH in the range of 7–8.5 while acidogenic bacteria prefer lower pH, the organic acids are diluted into the second stage at a controlled rate. Often a closed recirculation loop is provided to allow greater contact time for the unhydrolyzed organic matter. Fig. 13 shows a general layout for the multi-stage process, in which the first reactor has high solid and the second reactor has low solid content i.e. dry–wet configuration.

5.2.1. Multi-stage high-solid process

The Biopercolat process is a multi-stage high-solid process, in a liquefaction/hydrolysis reactor followed by a methanogenic upflow anaerobic sludge blanket reactor (UASB) with attached growth. Hydrolysis is carried out in the anaerobic zone, where limited amount of oxygen is supplied i.e under high solids and microaerophilic conditions. The aeration in the first stage and the attached growth reaction in the second provide for complete digestion at retention time of only 7 days.

The advocates of multi-stage high solid process cite the advantages of high OLR such as 15 kg VS/(m^3 day) for Biopercolat processes (MSHS). This is due to the fact that the higher biomass retention with attached biofilm increases the resistance of methanogens to high ammonium concentrations [79]. However, the

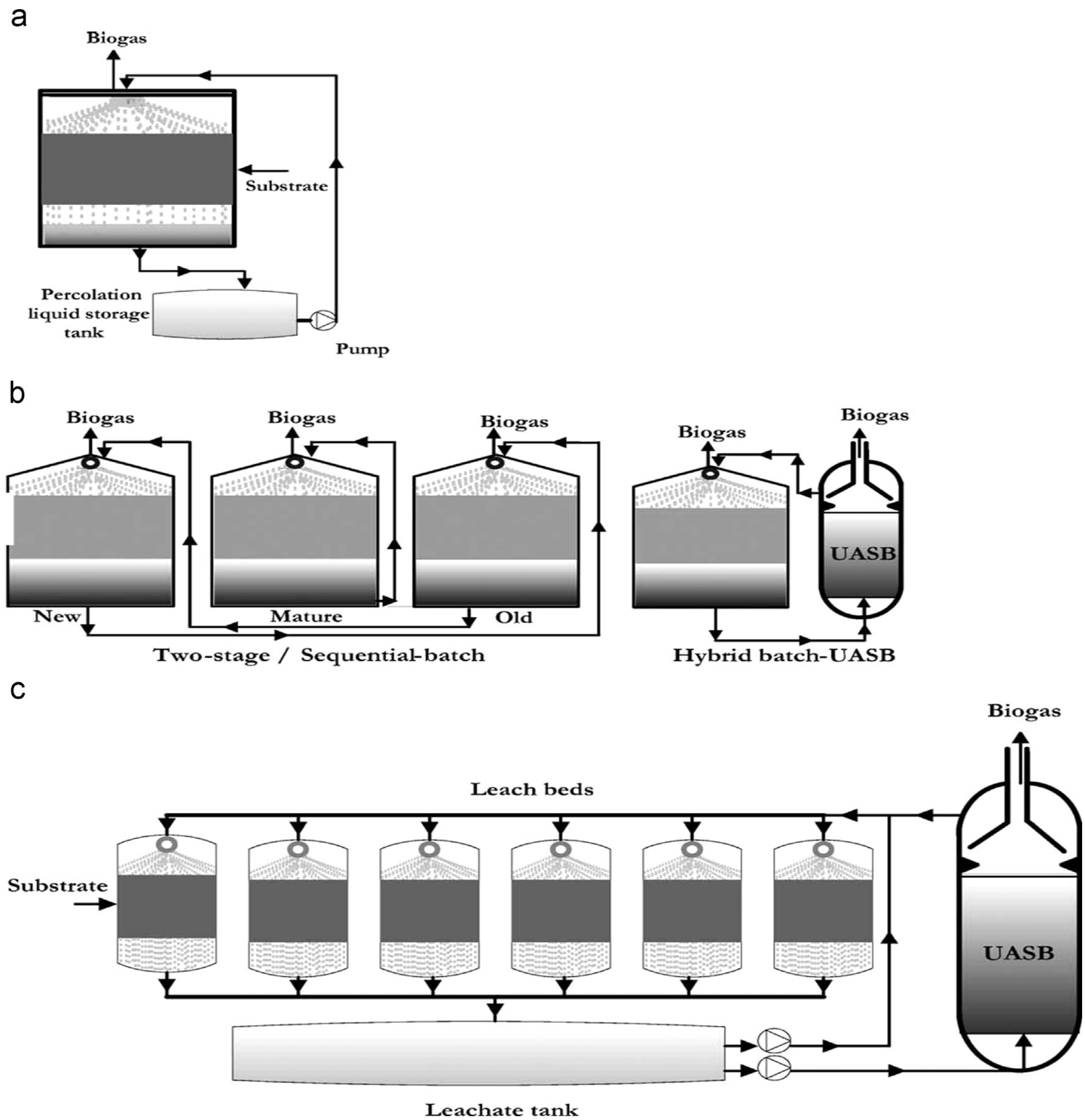

Fig. 15. (a) One-stage dry batch digester, (b) two-stage dry batch digesters and (c) sequencing fed leach bed digesters coupled with UASB [116].

application of multi-stage systems for treatment process is only about 10% of the current utilization [105]. Fig. 14 depicts an MSHS system by Linde-KCA, for commercial application with high solid content [112,113].

5.3. Batch and continuous reactors

This section gives a brief about batch and continuous reactors.

5.3.1. Batch reactors

The main advantages from batch reactors are that they are relatively technically simple and robust in nature, and have low maintenance requirements, low parasitic energy loss, and most importantly minimum capital cost [114]. However, they also have some drawbacks viz. land footprint requirement is large as compared to SSHS reactors because they are much shorter and have less OLR, deposition of material to the bottom which reduces the biogas yield which ultimately increases the risk of explosion while unloading the reactor. The total solid content in the typical batch system ranges from 30% to 40%. For reactions, batch reactors are loaded with fresh feedstock, discharged and then loaded with a new batch. The batch systems may appear as in-vessel landfills but have higher reaction rates and higher biogas yields that may be in the range of 50–100% of landfill ones because these reactors are operated at higher temperatures than those of landfills and the leachate is re-circulated continuously.

The batch reactors may be of three types – single stage batch system, sequential batch system and an upflow anaerobic sludge blanket (UASB) reactor [73]. A single-stage batch system [Fig. 15a] operates at mesophilic temperatures and consists of 14 concrete reactors each of 480 m^3 capacity. In this system, leachate is re-circulated to the top of the same reactor and the waste is mixed with inoculums before being fed to these unstirred reactors. The leachates are recycled to the top of each reactor after being collected in chambers under the reactors [115]. Mahnert et al. [116] examined the biogas and methane yield of fresh and ensiled grass species in a laboratory-scale batch digester. The highest biogas yields (0.83 and 0.86 $m^3\,kg^{-1}$ VS added) were found for perennial ryegrass and the lowest (0.72 and 0.65 $m^3\,kg^{-1}$ VS added) for fresh cocksfoot and

silage. The sequential batch [Fig. 15b] process contains two or more reactors. The leachate from the first reactor which contains a high level of organic acids is re-circulated to the second reactor, where methanogenesis occurs. The leachate of the second reactor, which contains little or no acid, is combined with pH buffering agents and re-circulated to the first reactor. This assures the inoculation between the first and second reactors. The third type of batch process is the hybrid batch–UASB [Fig. 15c] process, which is more or less similar to that of the multi-stage process with two reactors. In this type of reactor, the first reactor is a simple batch reactor but the second reactor which is also known as the methanogenic reactor is an upflow anaerobic sludge blanket (UASB) reactor [103].

5.3.2. Continuous reactors

In the continuous process, fresh material continuously enters the tank and an equal amount of digested material is removed. There are distinct stages of digestion throughout the batch process whereas equilibrium is achieved in the continuous process. With consistent feedstock input, all reactions occur at a fairly steady rate resulting in approximately constant biogas production. The structure for a continuous process can be identical to that of a batch process, a cylindrical tank with influent and effluent valves. Because there is constant movement, however, material inside the tank is mixed and does not become stratified. This allows for more optimal use of the tank volume [116]. The disadvantage of the continuous process is that the removed effluent is a combination of completely digested and partially digested material. To minimize the removal of partially digested material some designs dictate the path of the digestate inside the chamber, for example through the use of interior walls. The reported residence time for a continuous process is an average across the substrate. In the DAD process, this type reactors are designed in a plug-flow model [116].

6. Environmental impacts of DAD

Because all of the products of AD have valuable end uses there is no waste produced and therefore less use of landfills, where methane emissions create environmental damage. Other environmental benefits include improved water quality, renewable energy generation, reduced need for chemical fertilizers, and enhanced air quality due to less CO_2 emissions. The end products of AD are biogas and digestate, a moist solid which is normally dewatered to produce a liquid stream and a drier solid. The components of the biogas depend on the process of digestion, but are predominately methane and carbon dioxide in general. The solid is a humus-like, stable, organic material, the quality and subsequent use of which are determined by the characteristics of the feedstock to the AD process. Only soluble organics are degraded in the reactor so that other materials, such as glass or plastics, or trace elements, such as heavy metals or salts,

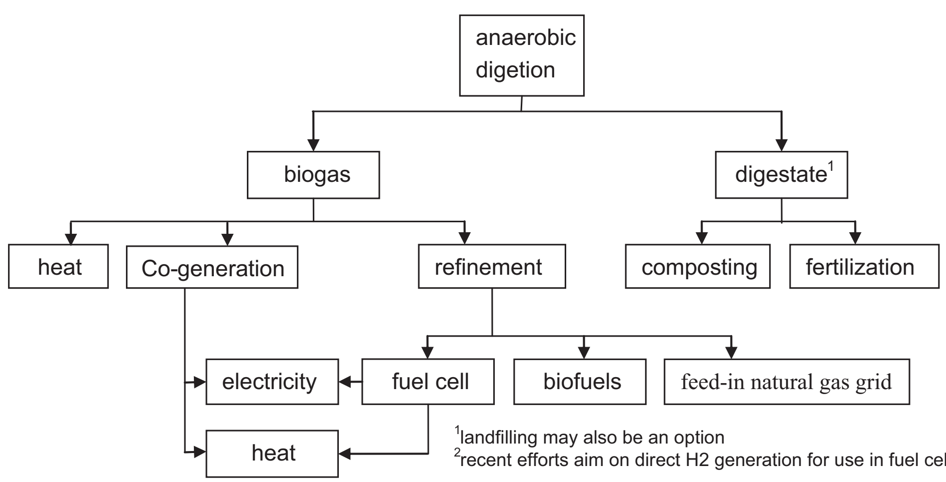

Fig. 16. Options for conversion and utilization of biogas and digestate in plants using renewables.

Table 6
Processes currently used for purifying and enriching biogas [128].

Biogas compound	Technique
Elimination of water demister	Cyclone separation Condensation Drying Adsorption onto silica
Elimination of H_2S aerobic biological oxidation	Adding $FeCl_3$ to the digester Adsorption onto Fe_2O_3 Absorption (NaOH) Absorption (iron solution) Membrane separation Biological filters Activated carbon Molecular sieving
Elimination of CO_2 pressure swing adsorption (PSA)	
Techniques based on physical absorption	
	Membrane separation
Techniques based on chemical absorption	
	Propane adding Cryogenisation

will be present in the solid if they entered in the feedstock. For these reasons, researchers have proposed innovative ideas and worked on the screening of useful products with highest yields and less harmful impacts on environment [117–120].

Among other advantages, energy recovery from renewable sources can help to reduce Green-House Gas (GHG) emissions. Unlike combustion of natural gas, liquefied gas, oil and coal, energy generation from biogas is an almost carbon neutral way to produce energy from regional available raw materials. The options for conversion and utilization of biogas and digestate in plants using renewables are presented in Fig. 16. Many of the European municipalities, based on the production of biogas, developed programs of solid waste valorization under the framework of new policies regarding waste management [117–120]. Rasi et al. [121] focused on the trace compounds of biogas from different biogas production plants. The authors pointed out that at the industrial level, in biogas currently produced from landfills and anaerobic digesters, main components of biogas are methane (CH_4) and carbon dioxide (CO_2) before purification. However, variable amounts of minor compounds such as hydrogen sulfide (H_2S), water (H_2O), and ammonia (NH_3) as well as many others could also be part of the biogas composition.

Yamulki [122] worked on nitrous oxide and methane emissions from stored solid manure and found that stored farmyard manure heaps are a source of nitrous oxide and methane emissions. Sneath et al. [123] found a CH_4 emission rate of 17.1 g cm^{-3} d^{-1} and 411 mg Nm^{-3} d^{-1}. Skiba et al. [124] found an emission rate of 1.4–38.6 g N_2O-Nm^{-3} d^{-1} for a 300 m^3 dung heap. Losses can be reduced by the means of continuous anaerobic digestion of daily produced solid manure. GHG emission in the case of solid manure storage may be higher than that of storage of slurry so that the continuous anaerobic digestion of daily produced solid manure is important. Schauss et al. [125] analyzed the emissions of anaerobically treated organic-matter. In this study, liquid and solid digestions residues were applied as fertilizer. Harvesting and fermenting of straw and intercrops were done in biogas reactors and application has been done as a fertilizer on the field. Low level of N_2O emissions and reduced losses (458 g N ha^{-1} a^{-1}) of the soil compared to the control variant (770 g N ha^{-1} a^{-1}) in case of winter wheat were found. Slightly decreased CH_4 uptake rate

Table 7
Toxicity values retained for the chemical risk evaluation [129].

Molecule	Inhalation URF $(mg/m^3)^{-1}$	RfC (mg/m^3)	CREL (mg/m^3)	Organization	Risk description
Acetaldehyde	2.7E−06			OEHHA	Nasal cancers in rats
Formaldehyde	1.3E−05			US-EPA	Squamous cell carcinoma in rats
Trichloroethene	2.0E−06			OEHHA	Hepatocellular adenoma and carcinoma incidence in mice
Vinyl chloride	7.8E−05			OEHHA	Lung cancers in mice
Tetrachloroethylene	5.90E−06			OEHHA	Hepatocellular adenoma and carcinoma incidence in mice
Tetrachloromethane	4.2E−05			OEHHA	Liver tumors in mice
1,4 dichlorobenzene	1.0E−05			OEHHA	Calculated from a cancer potency factor derived by CDHS
Benzene	2.9E−05			OEHHA	Human occupational exposure leukemia
Chromium	VI 0.15			OEHHA	Human lung cancer mortality data
Arsenic	4.3E−03			US-EPA	Human lung cancer
Nickel	4.0E−04			WHO	Human lung cancer
Cadmium	4.2E−03			OEHHA	Human lung cancer
Mercury			0.09	OEHHA	Effects on human nervous system
Hydrogen sulfide		2		US-EPA	
Hydrogen chloride			9	OEHHA	Effects on human respiratory system
Phosgene		0.3		US-EPA	
Hydrogen fluoride			14	OEHHA	

URF, Unit Risk Factor; RfC, reference concentration; CREL, chronic reference exposure level. US-EPA, United States Environmental Protection Agency; OEHHA, US-Office of Environmental Health Hazard Assessment; CDHS, California Department of Health Services; WHO, World Health Organization.

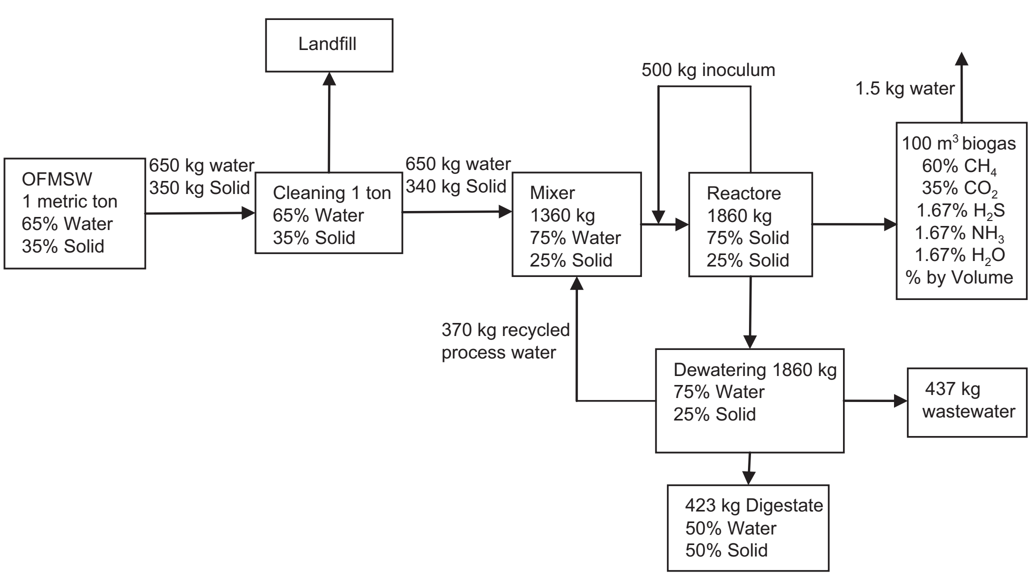

Fig. 17. Material balance in AD process [134].

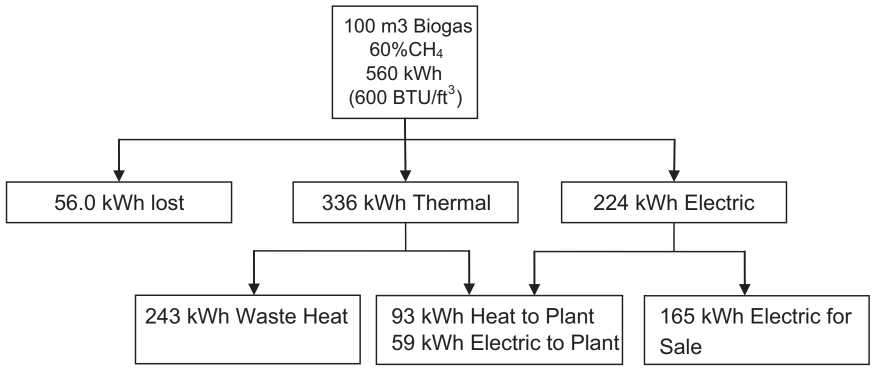

Fig. 18. Energy flow in AD process [134].

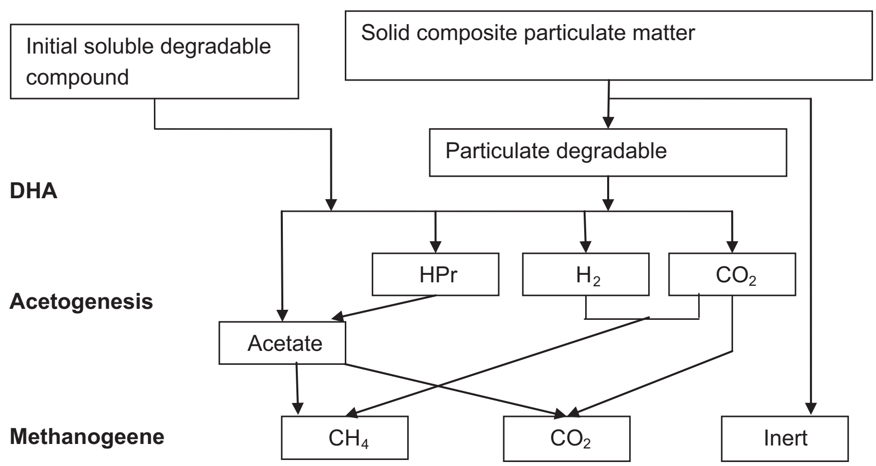

Fig. 19. Simplified dry digestion model proposed (HPr: propionic acid) by Bollon et al. [144].

($484\ g\ C\ ha^{-1}\ a^{-1}$) as compared to the controlled variant ($591\ g\ C\ ha^{-1}\ a^{-1}$) was found in the measurements of CH_4 fluxes. Wulf et al. [126] found that the anaerobic co-fermentation of organic MSW increased the biogas yield and helped simultaneously in the reduction of CO_2 emissions.

Dry fermentation residues can be anaerobically composted due to their high dry matter content. If an aerobic process heats the solid organic matter followed by anaerobic fermentation there is little positive environmental impact of DAD as compared to slurry biogas plants viz. pathogens are reduced by the high temperature during the aerobic process and for the following anaerobic process, the generated heat is used as process heat [127]. Table 6 summarizes the main technical processes currently used for purification and enrichment of biogas [128]. Ghinwa et al. [129] determined the microbiological and chemical compositions of different biogas types in order to conduct risk assessments of the potential health hazards associated with biogas used for cooking. It was found that if the biogas is produced from the fermentation of non-dangerous waste then as compared to natural gas processed biogas in the distribution network it did not present any additional chemical or microbiological risk to consumers. Table 7 shows the toxicity values for the chemical risk evaluation. Some other important environmental aspects associated with the DAD process are e.g. electricity generated from biogas is green because it causes no net carbon emissions to the atmosphere. Combustion of methane proceeds according to the equation

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{21}$$

Though carbon dioxide is a product of this reaction the source of the carbon is from biomass, not fossil fuels. In other words, the CO_2 released will subsequently be used by plants in photosynthesis to produce carbohydrates. These carbohydrates will be processed to form food, the scraps of which will be used as the fuel of the AD facility, thus closing the loop. The benefits of decreasing fossil fuel use are well documented and include reduced dependence on foreign fuel sources. The 75,000 tpa facility would generate approximately 7.5 million kWh each year, enough to supply 1250 homes [130] and displace 13,000 t carbon dioxide [131]. Similarly, use of digestate as a compost material for agriculture is a proven method to maintain or restore the quality of soils [132]. Compost has been proven to be effective globally, for example in southern Europe where it is a valuable method of tracking organic matter depletion, desertification and soil erosion [133].

7. Material and energy flow in DAD process with available models

Ostrem [134] has shown a typical flow of materials and energy for an anaerobic digestion system for material and energy balance as shown in Figs. 17 and 18 respectively. The moisture content of raw waste is normally between 50% and 65%, and so water must be added to raise it above 75%. This is provided by dewatering the final solid digestate and recirculating the water back to the mixing tank. High moisture is critical for feedstock in an AD plant so that it can be pumped. The material balance shows that this amount of additional water can be supplied entirely by recycled process water, saving money and resources for the plant.

The biogas is the energy carrier in the process, and its use is detailed in the energy balance shown in Fig. 19 by Ostrem [134]. Batstone [135] has strived for a standardization of model structure

and parameterization over the last couple of years. Two most widely used models for anaerobic digestion are the Anaerobic Digestion Model no. 1 (ADM1), developed by a task group for the International Water Association (IWA), and Siegriest Model [136]. The ADM1 has often been used as a framework model enabling researchers to focus on modifications for specific purposes. The model includes kinetics for disintegration of homogenous particles to carbohydrates, proteins and lipids, and hydrolysis of these particles to sugars, amino acids and LCFA. Whereas Siegriest is a slightly more simplified model oriented towards mixed sludge treatment. The main differences are the exclusion of valerate and butyrate as state variables. The hydrolysis is modeled as a single step process with first order kinetics with respect to the concentration of particulate matter; furthermore, the uptake and decay rates are higher than in the ADM1 model. The two models were constructed with different approaches: the Siegriest model parameters are based on experiments, whereas the ADM1 uses review consensus [135].

Lubken et al. [137] show the application and modification of Anaerobic Digestion Model no. 1 (ADM1) to simulate energy production of the digestion of cattle manure and renewable energy crops. This paper additionally presents an energy balance model, which enables the dynamic calculation of net energy production. The model was applied to a pilot-scale biogas reactor. It was found in a simulation study that a continuous feeding and splitting of the reactor feed into smaller heaps do not generally have a positive effect on the net energy yield. Energy losses were strongly influenced by the season. From the abovesaid discussions in the article's various sections, it can be concluded that AD is a complex system of biochemical and physical processes. Due to the complexity of the process it has been traditionally treated as a black box system, and optimization has been based on experience or trial and error methods. As experiments of anaerobic digestion processes are expensive and time-consuming, modeling can provide a useful tool for process understanding and optimization. Models have potentials for revealing non-linear behaviors of the system and to quantify the performance of alternative operational setups. Usually such processes contain a particular step, the so called rate-limiting or rate-determining step, which, being the slowest, limits the rate of the overall process [138]. Lawrence [139] defined limiting step as “that step which will cause process failure to occur under imposed conditions of kinetic stress“. The first attempts for modeling anaerobic digestion led to models describing only the limiting step. However, during a wide range of operating conditions, the limiting step is not always the same. It may depend on waste characteristics, hydraulic loading, temperature, C/N ratio, etc.

For general aspects on modeling for anaerobic digestion, Lyberatos and Skiadas [140] gave an extensive review. All the existing detailed anaerobic digestion models take into account particularly the importance of describing the behavior of anaerobic digesters. They concluded that some important factors should be evaluated from a modeling point of view, and the effect of the significant ones should be properly accounted for i.e. digester startup conditions; degree of acclimation to the fed wastewater; hydraulic loading; organic loading; biogas production per unit volume; concentration of inhibitors; availability of nutrients; cation concentration, especially Ca^{2+} and Mg^{2+}; and concentration and type of solids contained in the waste/wastewater.

As per the objective of this article, models involved in the solid state anaerobic digestion are also reviewed according to the availability of literature. Jha et al. [141] discussed and reviewed the kinetic modeling of the anaerobic degradation of solid organic wastes, which is increasingly needed for a better understanding of the performance of these systems. It is essential for the rational design and operation of biological waste treatment systems to predict the system stability, effluent quality, and waste stabilization. Kalyuzhnyi et al. [142] has developed a structured mathematical model of anaerobic solid state fermentation (ASSF), including multiple reaction stoichiometry, microbial growth kinetics, material balances, liquid–gas interactions and liquid phase equilibrium chemistry. The theoretical model is in agreement at a qualitative level with existing experimental studies of ASSF. Based on computer simulations that model influence of biodegradability and mass transfer intensity on the fermentation process stability, possible measures were proposed to prevent accumulation of VFAs inside the “seed“ particles beyond their assimilative methanogenic capacity. Viéitez et al. [143] developed a Monod-type product-formation model that was used to predict methane formation and to determine kinetic parameters for the methanogenic processes in a simulated landfill or methane reactors. Bollon et al. [144] developed a kinetic model to specifically assess the degradation of the organic fraction of municipal solid waste (OFMSW) in dry anaerobic digestion processes (Fig. 19). The model description was designed to include several aspects of dry digestion such as the presence of particulate matter and high solid content. The model was shown to simulate well batch degradation of acetate and methane production in dry mode.

8. Conclusions

DAD is a tool to transform the organic waste materials to quality based end-product with less input of water, less odor emissions, less nutrient runoff during storage and distributions of digester residues because there is no liquid mass transfer. It is an approach to degrade high solid content waste materials in an eco-friendly manner. The degradation of a waste material and the rate at which it is achieved depend on various environmental and operational conditions like material and energy flow with modeling, pilot scale conditions, pre- and post-treatments and reactor volumes. This technology needs to be properly optimized. Hence, it can be concluded that research opportunities in dry anaerobic digestion involve understanding the use of feedstock with operational parameters, control and presence of microorganisms with reactor design and operation, well-suited for the digestion environment. This review should help in setting up the process of DAD based on various approaches in developed, developing and underdeveloped countries to promote waste to energy route.

Acknowledgment

Sincere thanks are due to the Ministry of New and Renewable Energy Government of India the R&D activities.

References

[1] Venkateswara RP, Baral SS, Dey R, Mutnuri S. Biogas generation potential by anaerobic digestion for sustainable energy development in India. Renew Sust Energy Rev 2010;14:2086–94.
[2] Eugen A, cioablă, IONE I, Triftordai G. Experimental approach for biogas production from biowaste. Int. J. Energy Environ 2011;5:402–9.
[3] Singh J, Gu S. Biomass conversion to energy in India—a critique. Renew Sust Energy Rev 2010;14:1367–78.
[4] Raposo F, De la Rubia MA, Fernández-Cegrí V, Borja R. Anaerobic digestion of solid organic substrates in batch mode: an overview relating to methane yields and experimental procedures. Renew Sustain Energy Rev 2012;16:861–77.
[5] Fernández J, Pérez M, Romero LI. Effect of substrate concentration on dry mesophilic anaerobic digestion of organic fraction of municipal solid waste (OFMSW). Bioresour Technol 2008;99:6075–80.
[6] Cao Y, Pawłowski A. Sewage sludge-to-energy approaches based on anaerobic digestion and pyrolysis: brief overview and energy efficiency assessment. Renew Sustain Energy Rev 2012;16:1657–65.

[7] Bolzonella D, Innocenti L, Pavan P, Traverso P, Cecchi F. Semi-dry thermophilic anaerobic digestion of the organic fraction of municipal solid waste: focusing on the start-up phase. Bioresour Technol 2003;86:123–9.
[8] Brummeler ET. Full scale experience with the BIOCEL process. Water Sci Technol 2000;41:299–304.
[9] Liu G, Peng X, Long TR. Advance in high solid anaerobic digestion of organic fraction of munciple solid waste. J Cent South Univ Technol 2006;13:416–20.
[10] Liu ZG, Zhu HG, Wan GB, Zhang Y. Effect of ratio of manure to crop on dry anaerobic digestion for biogas production. J Chin Society Agric Eng 2009;25(4):151–7.
[11] Angelidaki I, Ahring BK. Effects of free long-chain fatty acids on thermophilic anaerobic digestion. Appl Microbiol Biotechnol 1992;37:808–12.
[12] Buffiere P, Loisel D, Ndelgenes B, Delgenes JP. Towards new indicators for the prediction of solid waste anaerobic digestion properties. Water Sci Technol 2006;53:233–41.
[13] Kothari R, Kumar V, Tyagi VV. Assessment of waste treatment and energy recovery from dairy industrial waste by anaerobic digestion. Environ Manag Sustain Dev 2011;2:1–6 (IIOAB special issue).
[14] Themelis NJ, Verma S. The better option: anaerobic digestion of organic waste in MSW. Waste Manag World 2004.
[15] Madigan MT, Martinko JM, Dunlap PV, Clark DP. Brock biology of microorganisms. 12th ed.Benjamin Cummings; 2009.
[16] Andrews JF. A mathematical model for the continuous culture of microorganisms utilizing inhibitory substrate. Biotechnol Bioeng 1968;10:707–23.
[17] Heuvel JCVD, Beeftink HH. Kinetic effect of simultaneous inhibition of substrate and product. Biotechnol Bioeng 1988;31:718–24.
[18] Shuler ML, Kargi F. Bioprocess engineering. 2nd ed. New Delhi: Prentice-Hall of India Private Limited; 2002.
[19] Veeken A, Kalyuzhnyl S, Schaff H, Hamelers B. Effect of pH and VFA on hydrolysis of organic solid waste. J Environ Eng (ASCE) 2000;126:1076–81.
[20] Veeken A, Hamelers B. Effect of temperature on hydrolysis rates of selected biowaste components. Bioresour Technol 1999;69:249–54.
[21] Patil JH, Raj MA, Gavimath CC, Mali BM. A study on effect of volatile fatty acid on biomethanation of water hyacinth. Int J Adv Biotechnol Res 2011:257–62.
[22] Montero B, Garcia-Morales JL, Sales D, Solera R. Evolution of microorganisms in thermophilic–dry anaerobic digestion. Bioresour Technol 2008;99:3233–43.
[23] Evans G. Biowaste and biological waste treatment. The Cromwell Press; 1-902916-08-5.
[24] Siegert I, Banks C. The effect of volatile fatty acid additions on the anaerobic digestion of cellulose and glucose in batch reactors. Process Biochem 2005;40(11):3412–8.
[25] Batstone DJ, Keller J. Angelidaki Ikalyuzhnyi SV, Pavlostathis SG, Rozzi A, Sanders WTM, et al. Anaerobic Digestion Model No. 1. A task group on mathematical modeling of anaerobic digestion process. IW A Scientific and Technical Report No. 13. London, UK: IW A Publishing; 2002.
[26] Singh RP, Tyagi VV, Allen T, Ibrahim MH, Kothari R. An overview for exploring the possibilities of energy generation from municipal solid waste (MSW) in Indian scenario. Renew Sustain Energy Rev 2011;15(9):4797–808.
[27] Fernandez J, Perez M, Romero LI. Effect of substrate concentration on dry mesophilic anaerobic digestion of organic fraction of municipal solid waste (OFMSW). Bioresour Technol 2008;99:6075–80.
[28] Drake HL, Daniel SL. Physiology of the thermophilic acetogen Moorella thermoacetica. Res Microbiol 2004;155:869–83.
[29] Xu K, Liu H, Du G, Chen J. Real-time PCR assays targeting formyltetrahydrofolate synthetase gene to enumerate acetogens in natural and engineered environments. Anaerobe 2009;15:204–13.
[30] Boone DR, Chynoweth DP, Mah RA, Smith PH, Wilkie AC. Ecology and microbiology of biogasification. Biomass Bioenergy 1993;5:191–202.
[31] Lo YC, Saratale GD, Chen WM, Bai MD, Chang JS. Isolation of cellulosehydrolytic bacteria and applications of the cellulolytic enzymes for cellulosic biohydrogen production. Enzym Microb Technol 2009;44:417–25.
[32] Kotsyurbenko OR, Glagolev MV, Nozhevnikova AN, Conrad R. Competition between homoacetogenic bacteria and methanogenic archaea for hydrogen at low temperature. FEMS Microbiol Ecol 2001;38:153–9.
[33] Fricke K, Santen H, Wallmann R, Huttner A, Dichtl N. Operating problems in anaerobic digestion plants resulting from nitrogen in MSW. Waste Manage 2007;27:30–43.
[34] Lee J, Song J, Hwang S. Effects of acid pre-treatment on bio hydrogen production and microbial communities during dark fermentation. Bioresour Technol 2009;100:1491–3.
[35] Fantozzi F, Buratti C. Biogas production from different substrates in an experimental Continuously Stirred Tank Reactor anaerobic digester. Bioresour Technol 2009;100:5783–9.
[36] Garcia JL, Patel BKC, Ollivier B. Taxonomic, phylogenetic and ecological diversity of methanogenic archaea. Anaerobe 2000;6:205–26.
[37] Ferry JG. Enzymology of one-carbon metabolism in methanogenic pathways. Microbiol Rev 1999;23:13–38.
[38] Thauer RK, Kaster AK, Seedorf H, Buckel W, Hedderich R. Methanogenic archaea: ecologically relevant differences in energy conservation. Nat Rev Microbiol 2008;6:579–91.
[39] Shankaranand VS, Ramesh MV, Lonsane BK. Idiosyncrasies of solid-state fermentation systems in the biosynthesis of metabolites by some bacterial and fungal cultures. Process Biochem 1992;27(1):33–6.
[40] Klocke M, Nettmann E, Bergmann I, Mundt K, Souidi K, Mumme J, et al. Characterization of the methanogenic Archaea within two-phase biogas reactor systems operated with plant biomass. Systematic Appl Microbiol 2008;31:190–5.
[41] Zhu C, Zhang J, Tang Y, Xu Z, Song R. Diversity of methanogenic archaea in a biogas reactor fed with swine feces as the mono-substrate by mcrA analysis. Microbiol Res 2011;66:27–35.
[42] Ike M, Inoue D, Miyano T, Liu TT, Sei K, Soda S, et al. Microbialpopulation dynamics during startup of a full-scale anaerobic digester treating industrial food waste in Kyoto eco-energy project. Bioresour Technol 2010;101:3952–7.
[43] Kim JK, Nhat L, Chun YN, Kim SW. Hydrogen production condition from food waste by dark fermentation with *Clostridium beijerinckii* KCTC 1785. Biotechnol Bioprocess Eng 2008;13:499–504.
[44] Steffen R, Szolar O, Braun R. Feedstocks for anaerobic digestion. Institute for Agrobiotechnology Tulln University of Agricultural Sciences Vienna; 2012. 〈http://www.adnett.org/dl_feedstocks.pdf〉 ([accessed 25.07.12]).
[45] Pantaleo A, De Gennaro B, Shah N. Assessment of optimal size of anaerobic co-digestion plants: an application to cattle farms in the province of Bari (Italy). Renew Sustain Energy Rev 2013;20:57–70.
[46] Fdez-Güelfoa LA, Álvarez-Gallegoa C, Salesb D, Romero Garcíaa LI. Dry–thermophilic anaerobic digestion of organic fraction of municipal solid waste: methane production modelling. Waste Manage 2012;32:382–8.
[47] Steffen R, Szolar O, Braun R. Feedstocks for anaerobic digestion. Report, Vienna: Institute for Agro-biotechnology, Tulln University of Agricultural Sciences; 1998.
[48] Mishima D, Tateda M, Ike M, Fujita M. Comparative study on chemical pretreatments to accelerate enzymatic hydrolysis of aquaticmacrophyte biomass used in water purification processes. Bioresour Technol 2006;97(16):2166–72.
[49] Petersson A, Liden G. Fed-batch cultivation of *Saccharomyces cerevisiae* on lignocellulosic hydrolyzate. Biotechnol Lett 2007;29(2):219–25.
[50] Schell DJ, Farmer J, Newman M, McMillan JD. Dilute-sulfuric acid pretreatment of corn stover in pilot-scale reactor – investigation of yields, kinetics, and enzymatic digestibilities of solids. Appl Biochem Biotechnol 2003;105:69–85.
[51] Chandra RP, Bura R, Mabee WE, Berlin A, Pan X, Saddler JN. Substrate pretreatment: the key to effective enzymatic hydrolysis of lignocellulosics. Biofuels 2007;108:67–93.
[52] Chang VS, Nagwani M, Holtzapple MT. Lime pretreatment of crop residues bagasse and wheat straw. Appl Biochem Biotechnol 1998;74(3):135–59.
[53] Kim TH, Kim JS, Sunwoo C, Lee YY. Pretreatment of corn stover by aqueous ammonia. Bioresour Technol 2003;90(1):39–47.
[54] Dale BE, Linden JC. Fermentable sugars from lignocellulosic materials—the state of pretreatment processes. Am Chem Soc 1985;190:151 (abstracts of papers).
[55] Mosier N, Hendrickson R, Ho N, Sedlak M, Ladisch MR. Optimization of pH controlled liquid hot water pretreatment of corn stover. Bioresour Technol 2005;96(18):1986–93.
[56] Liew LN, Shi J, Li Y. Enhancing the solid-state anaerobic digestion of fallen leaves through simultaneous alkaline treatment. Bioresour Technol 2011;102:8828–34.
[57] Teater C, Yue Z, MacLellan J, Liu Y, Liao W. Assessing solid digestate from anaerobic digestion as feedstock for ethanol production. Bioresour Technol 2011;102:1856–62.
[58] Chanakya HN, Venkatsubramaniyam R, Moda J. Fermentation and methanogenic characteristics of leafy biomass feedstocks in a solid phase biogas fermentaor. Bioresour Technol 1997;62:71–8.
[59] Kim DH, Oh SE. Continuous high-solids anaerobic co-digestion of organic solid wastes under mesophilic conditions. Waste Manage 2011;31:1943–8.
[60] U.S. Department of Energy [Internet]. Energy efficiency and renewable energy. Biomass Program, Feedstock Composition Glossary, Accessed June 15, 2004.
[61] Available from: 〈http://www.eere.energy.gov/biomass/feedstock_glossary.html〉.
[62] Carr N. Solid waste characterization. 1999 California Statewide Waste Disposal Characterization Study, California Waste Management Board. Available from: 〈http://www.ciwmb.ca.gov/wastechar/〉.
[63] Zhang R, El-Mashad HM, Hartman K, Wang F, Liu G, Choate C, et al. Characterization of food waste as feedstock for anaerobic digestion. Bioresour Technol 2007;98:929–35.
[64] Lissens G, Verstraete W, Albrecht T, Brunner G, Creuly C, Seon J. Advanced anaerobic bioconversion of lignocellulosic waste for bioregenerative life support following thermal water treatment and biodegradation by *Fibrobacter succinogenes*. Biodegradation 2004;15(3):173–83.
[65] Wellinger A. Process design of agricultural digesters. Nova Energie GmbH Elggerstrasse, Report, 1999.
[66] Sutter K, Wellinger A. Güllengrube als Biogasanlage. FAT-Berichte 1987;304:1–8.
[67] National Renewable Energy Laboratory (NREL), Colorado, US Data Summary of Municipal Waste Management Alternatives, X (1992).
[68] Fernández-Rodríguez J, Pérez M, Romero LI. Comparison of mesophilic and thermophilic dry anaerobic digestion of OFMSW: kinetic analysis. Chem Eng J 2013;232:59–64.
[69] Forster-Carneiro T, Pe´rez M, Romero LI, Sales D. Dry–thermophilic anaerobic digestion of organic fraction of the municipal solid waste: focusing on the inoculum sources. Bioresour Technol 2007;98:3195–203.
[70] Mashad HM, Zeeman G, Loon WKP, Bot GPA, Lettinga G. Effect of temperature and temperature fluctuation on thermophilic anaerobic digestion of cattle manure. Bioresour Technol 2004;45:191–201.

[71] Zeemann G, Sutter K, Vens K, Wellinger A. Psychrophilic digestion of dairy cattle and pig manure: start-up procedures of batch, fed-batch and CSTR-type digesters. Biol Wastes 1998;26:15–31.
[72] Wellinger A, Lindberg A. Biogas upgrading and utilisation. IEA Bioenergy Task 1999;24:18.
[73] Fdez.-Güelfo LA, Álvarez-Gallego C, Sales Márquez D, Romero García LI. Dry–thermophilic anaerobic digestion of simulated organic fraction of municipal solid waste: process modeling. Bioresour Technol 2011;102:606–11.
[74] Dong L, Zhenhong Y, Yongming S. Semi-dry mesophilic anaerobic digestion of water sorted organic fraction of municipal solid waste (WS-OFMSW). Bioresour Technol 2010;101:2722–8.
[75] Shu-guang LU, Imai Tsuyoshi, Ukita Masao, Masahiko Sekine. Start-up performances of dry anaerobic mesophilic and thermophilic digestions of organic solid wastes. J. Environ Sci 2007;19:416–20.
[76] Hartmann H, Ahring BK. Strategies for the anaerobic digestion of the organic fraction of municipal solid waste: an overview. Water Sci Technol 2006;53(8):7–22.
[77] Hartmann H, Ahring BK. Anaerobic digestion of the organic fraction of municipal solid waste: influence of co-digestion with manure. Water Res 2005;39(8):1543–52.
[78] Bolzonella D, Innocenti L, Pavan P, Traverso P, Cecchi F. Semi-dry thermophilic anaerobic digestion of the organic fraction of municipal solid waste: focusing on the start-up phase. Bioresour Technol 2003;86:123–9.
[79] Kim M, Ahn YH, Speece RE. Comparative process stability and efficiency of anaerobic digestion, mesophilic vs. thermophilic. Water Res 2002;36(17):4369–85.
[80] Kuo WC, Lu HY. A complete resource recovery of the thermophilic anaerobic digestion. In: Proceedings of the 10th congress on anaerobic digestion, 2004, vol. 4. p. 1663–5.
[81] De Baere L. Anaerobic digestion of solid waste: state-of-the-art. Water Sci Technol 2000;41(3):283–90.
[82] Parkin GF, Owen WF. Fundamentals of anaerobic-digestion of waste-water sludges. J Environ Eng-ASCE 1986;112(5):867–920.
[83] Yen HW, Chiu CH. The influences of aerobic–dark and anaerobic–light cultivation on CoQ (10) production by *Rhodobacter sphaeroides* in the submerged fermenter. Enzym Microb Technol 2007;41(5):600–4.
[84] Weiland P. State of the art of solid-state digestion – recent developments. In: Rohstoffe FN, editor. Solid-state digestion – state of the art and further R&D requirements, 24. Gulzower Fachgespräche; 2006. p. 22–38.
[85] Pang YZ, Liu YP, Li XJ, Wang KS, Yuan HR. Improving biodegradability and biogas production of corn stover through sodium hydroxide solid state pretreatment. Energy Fuels 2008;22(4):2761–6.
[86] Bouallagui H, Lahdheb H, Romdan E, Rachdi B, Hamdi M. Improvement of fruit and vegetable waste anaerobic digestion performance and stability with co-substrates addition. J Environ Manage 2009;90:1844–9 (a).
[87] Romano RT, Zhang RH. Co-digestion of onion juice and wastewater sludge using an anaerobic mixed biofilm reactor. Bioresour Technol 2008;99(3):631–7.
[88] Zhu J, Li Y. Experimental study on solid state anaerobic digestion of organic waste for methane production. In: Proceedings of the 2009 annual ASABE meeting, 2009.
[89] Huber H, Thomm M, Konig H, Thies G, Stetter KO. Methanococeus hermolithotrophicus, a novel thermophilic lithotrophic methanogen. Arch Microbiol 1982;132:47–50.
[90] Yang ST, Okos MR. Kinetic study and mathematical modeling of methanogenesis of acetate using pure cultures of methanogens. Biotechnol Bioeng 1987;30:661–7.
[91] Lee DH, Behera SK, Kim J, Park HS. Methane production potential of leachate generated from Korean food waste recycling facilities: a lab scale study. Waste Manage 2009;29:876–82.
[92] Kim J, Park C, Kim TH, Lee M, Kim S, Kim SW, et al. Effects of various pretreatments for enhanced anaerobic digestion with waste activated sludge. J Biosci Bioeng 2003;95:271–5.
[93] Park Y, Tsuno H, Hidaka T, Cheon J. Evaluation of operational parameters in thermophilic acid fermentation of kitchen waste. J Mater Cycl Waste Mange 2008;10:46–52.
[94] Liu C, Yuan X, Zeng G, Li W, Li J. Prediction of methane yield at optimum pH for anaerobic digestion of organic fraction of municipal solid waste. Bioresour Technol 2008;99:882–8.
[95] Agdag ON, Sponza DT. Co-digestion of mixed industrial sludge with municipal solid wastes in anaerobic simulated landfilling bioreactors. J Hazard Mater 2007;140:75–85.
[96] Ward AJ, Hobbs PJ, Holliman PJ, Jones DL. Optimization of the anaerobic digestion of agricultural resources. Bioresour Technol 2008;99:7928–40.
[97] Wellinger A. Process design of agricultural digesters. Nova Energie GmbH Elggerstrasse, Report, 1999.
[98] Schaefer SH. Retooling the ethanol industry: thermophilic anaerobic digestion of thin stillage for methane production and pollution prevention. (Master thesis). US: Department of Civil Engineering, IOWA State University; 2006.
[99] Schaefer MT, Sung S. Retooling the ethanol industry: thermophilic anaerobic digestion of thin stillage for methane production and pollution prevention. Water Environ Res 2008;80:101–8.
[100] Regional Information Service Centre for South East Asia on Appropriate Technology (RISE-AT). Review of current status of Anaerobic Digestion Technology for treatment of MSW. November 1998.
[101] Tchobanoglous G, Theisen H, Vigil S. Intergrated solid waste management. New York: McGraw-Hill; 1993 (chapter 9).
[102] Fernandez J, Perez M, Romero LI. Effect of substrate concentration on dry mesophilic anaerobic digestion of organic fraction of municipal solid waste (OFMSW). Bioresour Technol 2008;99(14):6075–80.
[103] Verma S. Anaerobic digestion of biodegradable organics in municipal solid waste [Master of Science thesis]. Department of Earth and Environmental Engineering, Henry Krumb School of Mines, Fu Foundation School of Engineering and Applied Science, Columbia University, , 2002.
[104] Vandevivere P, De Baere L, Verstraete W. Types of anaerobic digester for solid wastes. In: Mata-Alvarez J, editor. Biomethanization of the organic fraction of municipal solid wastes. London: IWA Press; 2003. p. 112–40.
[105] De Baere L. Anaerobic digestion of solid waste: state of the art. Water Sci Technol 1999;41(3):283–90.
[106] Rapport J, Zhang R, Jenkins BM, Williams RB. Current anaerobic digestion technologies used for treatment of municipal organic solid waste. California Environmental Protection Agency; 2008. 〈http://www.calrecycle.ca.gov/Publications/Organics/2008011.pdf〉 (Available at).
[107] Angelidaki I, Ellegaard L, Ahring BK. Applications of the Anaerobic Digestion Process. Adv Biochem Eng/Biotechnol 2003:82.
[108] Si-Kyung C, Wan-Taek I, Dong-Hoon K, Moon-Hwan K, Hang-Sik S, Sae-Eun O. Dry anaerobic digestion of food waste under mesophilic conditions: performance and methanogenic community analysis. Bioresour Technol 2013;131:210–7.
[109] De Baere L. Partial stream digestion of residual municipal solid waste. Water Sci Technol 2008;7(7):1073–7.
[110] Martin DJ, Potts LGA, Heslop VA. Reaction mechanisms in solid-state anaerobic digestion I. The reaction front hypothesis. Process Saf Environ Prot 2003;81(B3):171–9.
[111] Liu TC, Ghosh S. Phase separation during anaerobic fermentation of solid substrates in an innovative plug-flow reactor. Water Sci Technol 1997;36(6-7):303–10.
[112] Nkemka VN, Murto M. Two-stage anaerobic dry digestion of blue mussel and reed. Renw Energy 2013;50:359–64.
[113] Nichols CE. Overview of anaerobic digestion technologies in Europe. BioCycle 2004;45(1):47–53.
[114] Williams RB, Davis UC. Technology assessment for advanced biomass power generation. PIER Consultation Report. Sacramento, CA: California Energy Commission; 2005.
[115] Schafer W, Lehto M, Teye F. Dry anaerobic digestion for organic residues on farm – a feasibility study. Finland: MTT Agrifood Research; 2006.
[116] Mahnert P, Heiermann M, Linke B. Batch- and semi-continuous production from different grass species. Agric Eng Int 2005;7.
[117] Rajeshwari KV, Balakrishnan M, Kansale A, Lata K, Kishore VVN. State-of-the art of anaerobic digestion technology for industrial wastewater treatment. Renew Sust Energy Rev 2000;4:135–56.
[118] Gikas P. Commissioning of the gigantic anaerobic sludge digesters at the wastewater treatment plant of Athens. Environ Technol 2008;29:131–9.
[119] Tsai WT. Bioenergy from landfill gas (LFG) in Taiwan. Renew Sust Energy Rev 2007;11:331–44.
[120] Commission of the European Communities. Landfill gas from environment to energy. Belgium, 1997.
[121] Rasi S, Veijanen A, Rintala J. Trace compounds of biogas from different biogas production plants. Energy 2007;32:1375–80.
[122] Yamulki S. Effect of straw addition on nitrous oxide and methane emissions from stored farmyard manures. Agric Ecosyst Environ 2006;112:178–85.
[123] Sneath R, Beline F, Hilhorst M, Pieu P. Monitoring GHG emission from manure stores on organic and conventional dairy farms. Agric Ecosyst Environ 2006;112:122–8.
[124] Skiba U, DiMarco C, Hargreaves K, Sneath R, Mcartney L. Nitrous oxide emission from a dung heap measured by chambers and plume method. Agric Ecosyst Environ 2006;112:135–9.
[125] Schauss K, Ratering S, Schnell S. Impact of fermented organic fertilizers on trace gas emissions in organic agriculture 2005.
[126] Wulf S, Jager P, Dohler H. Balancing of green house gas emissions and economic efficiency for biogas production through anaerobic co-fermentation of slurry with organic waste. Agric Ecosyst Environ 2005;112:178–85.
[127] Schafer W, Lehto M, Teye F. Dry anaerobic digestion of organic residues on-farm – feasibility study. Agrifood Research Reports, 2006. p. 77.
[128] AD-NETT (Dutch Energy). Anaerobic digestion of agro-industrial wastes: information networks. Technical Summary on gas treatment. Available from: 〈http://agrienvarchive.ca/bioenergy/download/AD_techsum_biogas_AD-NETT.Pdf〉, Project FAIR-CT96-2083 (DG12-SSMI), The Netherlands, 2000. p. 27.
[129] Ghinwa MN, Alary R, Bajeat P, Bellenfant G, Godon JJ, Jaeg JP, et al. Assessment of biogas potential hazards. Renew Energy 2011;36:3445–51.
[130] Department of Energy. Emissions of greenhouse gases in the United States. Greenhouse gas emissions from management of selected materials in municipal solid waste, EPA (2002), 2001.
[131] Brummeler ET. Full scale experience with the BIOCEL process. Water Sci Technol 2000;41:299–304.
[132] Bindu T, Ramasamy EV. High-solids anaerobic digestion for the recovery of energy and manure from Taro (*Colocasia esculenta*). J Solid Waste Technol Manage 2005;31(2):69–77.
[133] 〈http://www.europa2004.it/〉.

[134] Ostrem K. Greening waste: anaerobic digestion for treating the organic fraction of municipal solid wastes. (MS thesis). Columbia University; 2004.

[135] Batstone DJ. Mathematical modelling of anaerobic reactors treating domestic wastewater: rational criteria for model use. Rev Environ Sci Bio/Technol 2006;5:57–71.

[136] Siegriest H, Vogt D, Garcia-Heras JL, Gujer W. Mathematical model for meso- and thermophilic anaerobic sewage sludge digestion. Environ Sci Technol 2002;36:1113–23.

[137] Lubken M, Wichern M, Schlattmann M, Gronauer A, Horn H. Modelling the energy balance of an anaerobic digester fed with cattle manure and renewable energy crops. Water Res 2007;41:4085–96.

[138] Hill Jr. CG. An introduction to chemical engineering kinetics and reactor design. New York: Wiley; 1977.

[139] Lawrence AW. Application of process kinetics to design of anaerobic processes. In: Pohland FG, editor. Anaerobic biological treatment processes. Advances in Chemistry, vol. 105. Washington, DC: American Chemical Society; 1971. p. 163–89.

[140] Lyberators G, Skiadas IV. Modelling of anaerobic digestion – a review. Global Nest Int J 1999;1(2):63–76.

[141] Jha AK, Li J, Nies L, Zhang L. Research advances in dry anaerobic digestion process of solid organic wastes. Afr J Biotechnol 2011;10(65):14242–53.

[142] Kalyuzhnyi S, Veeken A, Hamelers B. Two-particle model of anaerobic solid state fermentation. Water Sci Technol 2000;41(3):43–50.

[143] Viéitez ER, Mosquera J, Ghosh S. Kinetics of accelerated solid state fermentation of organic-rich municipal solid waste. Water Sci Technol 2000;41(3):231–8.

[144] Bollon J, Le-hyaric R, Benbelkacem H, Buffiere P. Development of a kinetic model for anaerobic dry digestion processes: focus on acetate degradation and moisture content. Biochem Eng J 2011;56:212–8.